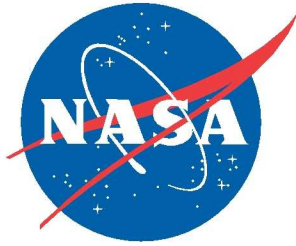


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Space Transportation System (STS)-117 External Tank (ET)-124 Hail Damage Repair Assessment

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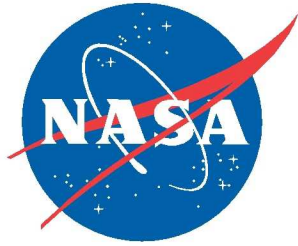
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Space Transportation System (STS)-117 External Tank (ET)-124 Hail Damage Repair Assessment

May 24, 2007

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Approval and Document Revision History

Approved:	Original signature on file <hr style="border: 0; border-top: 1px solid black;"/> NESC Director	12/10/07 <hr style="border: 0; border-top: 1px solid black;"/> Date
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Version	Description of Revision	Author	Effective Date
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Volume I: Assessment Report


1.0 Authorization and Notification

The assessment was requested and approved out-of-board on March 5, 2007 by authority of the Director, NASA Engineering and Safety Center (NESC). The NESC team was chartered by the NASA Office of Chief Engineer (OCE), and the Associate Administrator (AA) Space Operations Mission Directorate (SOMD) to assess hail damage repair efforts on the Space Transportation System (STS)-117 External Tank (ET)-124. Mr. Tim Wilson, Deputy Director NESC, was the responsible lead for this assessment. The four key stakeholders for this investigation are Mr. Wayne Hale, Space Shuttle Program (SSP) Manager at the Johnson Space Center in Houston, Texas; Mr. Chris Scolese, NASA Chief Engineer at NASA's Headquarters in Washington, D.C.; Mr. William Gerstenmaier, AA SOMD at NASA's Headquarters in Washington, D.C.; and Mr. Bryan O'Connor, Chief Safety and Mission Assurance (S&MA) Officer at NASA Headquarters in Washington, D.C.

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3.0 List of Team Members

Name	Discipline	Organization/Location
Core Team		
Tim Wilson	NESC Deputy Director/ Lead	LaRC
Tim Barth	NESC Systems Engineering Office (SEO), Human Factors	KSC
Steven Gentz	NESC Principal Engineer	LaRC
Cody Flowers	NESC Management and Technical Support Office (MTSO) Program Analyst	LaRC
David Hamilton	NESC Chief Engineer for JSC	JSC
Fred Martin	NESC Aerosciences Technical Discipline Team (TDT)	JSC
Stephen Minute	NESC Chief Engineer for KSC	KSC
Cynthia Null	NASA Technical Fellow, Human Factors	ARC
Charles Schafer	NESC Chief Engineer for MSFC	MSFC
Eugene Unger	NESC Fluids, Life Support, and Thermal TDT	JSC
Administrative Support Personnel		
Jessica A. Woods-Vedeler	Technical Assistant to the NESC Director	LaRC
Lisa Behun	Planning & Control Analyst	LaRC -Swales
Christina Cooper	Technical Writer	LaRC - Swales

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4.0 Executive Summary

Severe thunderstorms with associated hail and high winds struck the STS-117 stack on February 26, 2007. Peak winds were recorded at 62 knots with hail sizes ranging from 0.3 inch to 0.8 inch in diameter. As a result of the storm, the North Carolina Foam Institute (NCFI) type 24-124 Thermal Protection System (TPS) foam on the liquid oxygen (LO2) ogive acreage incurred significant impact damage. The NCFI on the ET intertank and the liquid hydrogen (LH2) acreage sustained hail damage. The Polymer Development Laboratory (PDL)-1034 foam of the LO2 ice frost ramps (IFRs) and the Super-Lightweight Ablator (SLA) of the LO2 cable tray also suffered minor damage.

NESC was asked to assess the technical feasibility of repairing the ET TPS, the reasonableness of conducting those repairs with the vehicle in a vertical, integrated configuration at the Kennedy Space Center (KSC) Vehicle Assemble Building (VAB), and to address attendant human factors considerations including worker fatigue and the potential for error. As the assessment progressed, the latter question evolved to a human factors assessment of the KSC work environment and adequacy of the process controls applied to PDL-type standard repairs.

ET-124 was subjected to a comprehensive visual inspection and repairs were executed to criteria documented in the ET Post-Build Acceptance and In-Process Re-Work Requirements Manual, Offsite, 80901019010 (9010). The 9010 requirements were modified in some instances to accommodate the high volume of repairs required for ET-124, and NESC reviewed and concurred with these modifications. The bulk of the damage was assessed and processed in one of three standard-repair categories: “use-as-is,” (minimal or no rework required), “sand-and-blend” or “PDL pour.” Hand-packed SLA was used to repair damage to the cable trays. Two areas of the LO2 tank, one just aft of the composite nose cap and the other in the aft section, were repaired using a non-standard BX-265 manual spray over the NCFI 24-124. This non-standard repair technique is similar to that used where the Protuberance Air Load (PAL) ramps were removed from the intertank and the LO2 and LH2 tanks.


NESC participated in technical discussions surrounding the inspections, repair categorization, and the repair processes and reviewed supporting planning, testing, and analyses. Key questions concerning the debris potential posed by undetected crushed foam remaining on ET-124 and adequacy of the various repair techniques were addressed. Recommendations were forwarded to the ET Project as the work progressed and all but one of the recommendations was implemented. NESC concurred with flying ET-124 on the STS-117 mission as-repaired.

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5.0 Assessment Plan

This assessment was conducted to evaluate the STS-117 ET-124 TPS hail damage repair effort. The task had three primary elements: (1) Evaluate the technical feasibility of repairing the damaged TPS foam, (2) assess the reasonableness of conducting those repairs with the vehicle in a vertical, integrated configuration at the KSC VAB, and (3) address attendant human factors considerations including worker fatigue and the potential for error. As the assessment progressed, the latter question evolved to a human factors assessment of the KSC work environment and adequacy of the process controls applied to PDL-type standard repairs.

Team members participated in planning and review meetings and maintained informal communication with ET Project management. The team participated in several Technical Interchange Meetings (TIM) and relevant ET Project review boards, most notably the ET Chief Engineer's Review Board (CERB). Team members evaluated the effectiveness of verification testing and analysis performed by the ET Project. A limited amount of independent analysis was performed by the NESC to confirm flight rationale for non-standard repair processes and to evaluate flight risk associated with prelaunch icing and thermal conditions during ascent.

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6.0 Description of the Problem and Approach

6.1 Problem Description


Severe thunderstorms with associated hail and high winds struck the STS-117 stack on February 26, 2007 while at Launch Pad 39. Peak winds were recorded at 62 knots with hail size ranging from 0.3 inch to 0.8 inch in diameter as shown in Figure 6.1-1. The NCFI 24-124 foam on the LO2 tank ogive acreage and the ET intertank incurred significant damage. NCFI on the ET intertank and PDL 1034 foam of the LO2 IFRs suffered minor damage, as did the LO2 tank cable tray SLA. An example of the resulting damage is shown in Figure 6.1-2.



Figure 6.1-1. Hail from the February 26, 2007 storm [ref. 26]



Figure 6.1-2. Example of Hail Damage to ET-124 TPS [ref. 27]

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In the initial damage assessment [ref. 3], the ET Project reported that the nose cone and machined surface of the LO2 ogive TPS had suffered a significant number of impacts. As Figure 6.1-3 depicts, impact damage to ET-124 was sustained around the entire circumference with the heaviest concentration on the +Z side with more than 1200 hits. There were numerous areas of damaged foam in the LO2 tank acreage TPS with the heaviest concentration in the +Z and -Y quadrants. Minor damage was observed on the inboard side of all LO2 IFRs with crushed foam observed on the IFRs at stations Xt-634 and Xt-676. Numerous areas of damaged NCFI were observed in the intertank area with the heaviest sustained in the -Z quadrant. Additional less severe damage was also observed in the +Z quadrant. Fewer than 12 hits were observed on the LH2 acreage TPS. Minor damage was observed on the -Y ET / Solid Rocket Booster (SRB) ramp aft fairing and cable tray and on the forward face of the LH2 IFRs.

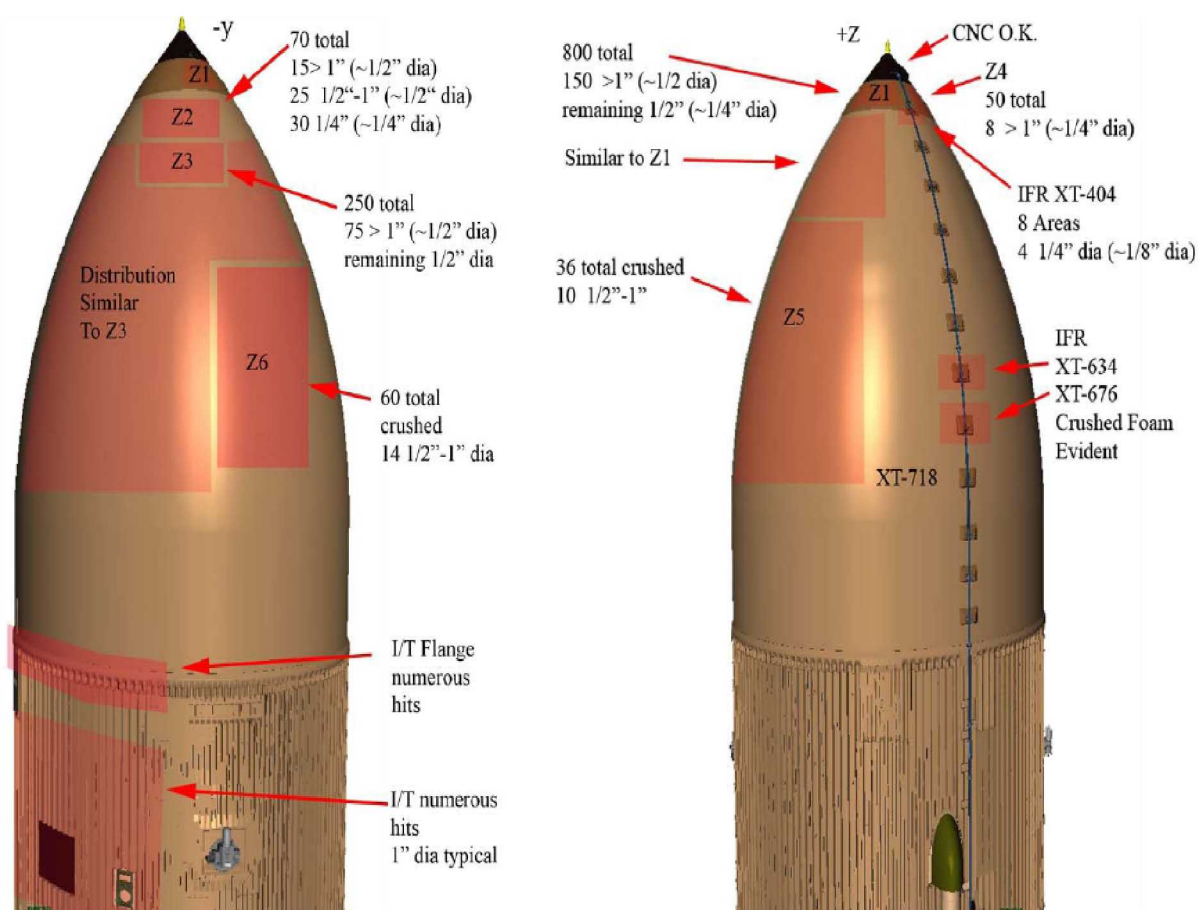



Figure 6.1-3. Initial Assessment of Hail Damage to ET-124 [ref. 4]

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6.2 Approach

ET Project performed detailed inspections of the tank and documented the location and extent of the damage. Inspections addressed all TPS surfaces and exposed composite and metallic components. Repair plans were developed to return ET-124 to a configuration meeting the requirements documented in the ET Post-Build Acceptance and In-Process Re-Work Requirements Manual, Offsite, 80901019010 (referred to herein as “9010”). Some variances from 9010 requirements were accepted by ET Project Material Review Board (MRB) action to reduce the number and invasiveness of repairs and minimize removal of undamaged TPS material. Previously validated standard repair techniques were implemented wherever possible.

6.2.1 Damage Inspection

The ET-124 impact damage inspection involved visual and tactile inspection of the tank surfaces and defects by experienced KSC United Space Alliance (USA) and Lockheed-Martin Space Systems Company (LMSSC) personnel [ref. 11]. A detailed TPS inspection grid was developed and an attributes database establishing to catalog individual impact sites and disposition of repairs. A summary is presented in Table 6.2-1 [ref. 25].

Exposed polymer matrix composite (PMC) hardware (the nose cap, intertank access door, and LO2 feedline fairing) were subjected to thermography non-destructive evaluation (NDE) with the results compared to the baseline inspection data.


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Table 6.2-1. STS-117 Hail Damage and Disposition

PR #	Description	Repair Type	Qty
ET-124-TS-0014	LO2 Tank TPS	BX-265	450
		Nodule Only	8
		PDL Repair	940
		Sand and Blend	888
		Use As Repaired	208
ET-124-TS-0015	+Y Aft Fairing	Use As Repaired	19
ET-124-TS-0016	-Y Aft Fairing	Use As Repaired	6
ET-124-TS-0017	SRB Pal Ramps	Use As Repaired	1
ET-124-TS-0018	Ice Frost Ramps C/O	Use As Repaired	6
ET-124-TS-0019	Ice Frost Ramps TPS	Use As Repaired	4
ET-124-TS-0022	LH2 Tank TPS	Nodule Only	2
		PDL Repair	19
		Use As Repaired	1
ET-124-TS-0023	Intertank TPS	PDL Repair	76
ET-124-TS-0024	LO2 Intertank Flange	Use As Repaired	105
ET-124-TS-0025	LH2 Tank Flange	Use As Repaired	5
ET-124-TS-0026	Vertical Strut	Use As Repaired	23
ET-124-TS-0027	Vertical Strut Cable Tray	Use As Repaired	23
ET-124-TS-0028	Umbilical Cable Tray	Use As Repaired	4
TOTAL			2788

6.2.2 Damage Disposition

The flowchart in Figure 6.2-1 outlines the initial plan for dispositioning TPS damage [ref. 9]. If the damage was superficial (cosmetic only), no repair was performed. If the damage depth was less than 0.3 inch, the crushed NCFI was removed and no further repair performed. PDL 1034 repairs were performed on damage greater than 0.3 inch in depth. Surface roughness and waviness criteria outlined in 9010 were modified to minimize the amount of sanding required. In two locations where size and density of PDL repairs would have resulted in violation of 9010 or pertinent Interface Control Document (ICD) requirements, large-area BX-265 spray repairs were performed. Minor violations of 9010 were accepted by MRB disposition on a case-by-case basis.

Minimum NCFI thickness criteria were revised downward slightly to minimize the number of PDL repairs required in the LO2 tank acreage foam. Specifically, the foam thickness criteria for acreage areas on ET-124 in the No-Ice and Ice Limitation zones were reduced to the minimums required to maintain an 85 percent launch probability between May and October. The minimum thickness criterion was reduced to 0.8 inch in the LO2 tank No-Ice zone which included a 0.1 inch thickness buffer to protect against any undetected crushed foam. The minimum thickness criterion was changed to 0.6 inch in the LO2 Ice-Limitation zone which also includes a 0.1 inch

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buffer. The minimum NCFI thickness of the LH2 tank Ice Limitation zone was changed to 0.88 inch.

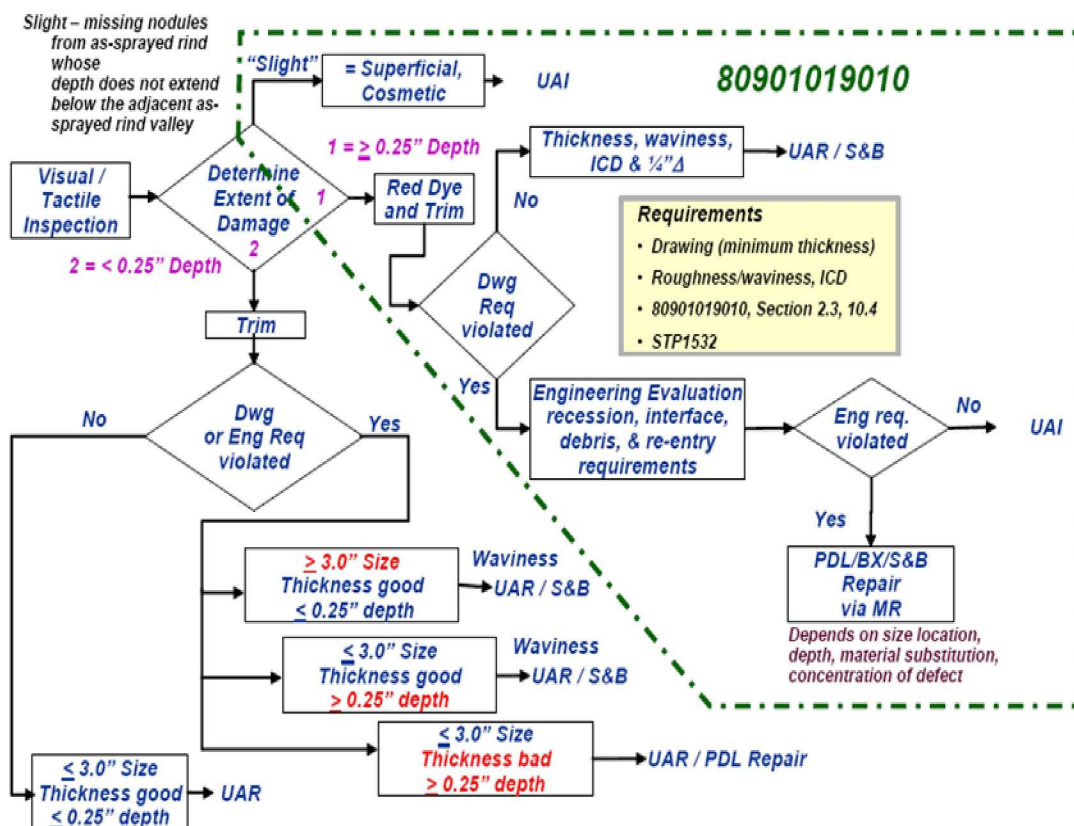



Figure 6.2-1. Preliminary Roadmap for ET-124 Repair Evaluation Process [ref. 9]

6.2.3 Repair Execution

6.2.3.1 Sand and Blend

Crushed foam was removed from damage locations less than 0.25 inch in depth and the remaining NCFI thickness evaluated. Sand and blend repairs were implemented at locations where the remaining TPS was sufficient to meet the revised minimum foam thickness criteria. While the 9010 document specifies a 16:1 diameter-to-depth ratio corresponding to a wall angle of approximately 7.5 degrees for repairs of this type, the criteria was modified for ET-124 to minimize removal of adjacent NCFI. The edges of defects up to 0.1 inch deep were slightly rounded. Defects greater than 0.1 inch deep were blended by sanding foam from an area extending no more than about 0.5 inch from the edge of the damage site. Steeper-than-normal wall angles were created in both instances. In another variation from the 9010 requirements, red

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dye was not applied to defects before the crushed NCFI was removed. If the final defect depth did not exceed 0.3 inch and no crack-like indications were evident, red dye was not applied after the sand-and-blend repair was completed. The result of these variations is an increase in the potential for day-of-launch ice formation at sand and blend repair locations, and an increased risk for undetected crushed foam at some locations.

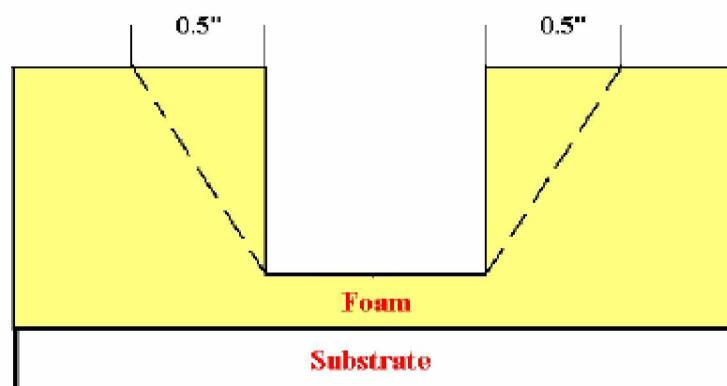


Figure 6.2-2. Sand and Blend Wall Angles for Defects > 0.1” Deep [ref. 24]


6.2.3.2 PDL Repairs

A PDL repair was performed if the acreage TPS thickness remaining under the defect was less than the required TPS minimum. If damage was visible, the degraded NCFI was removed with a grinder and the surface was sanded and cleaned. Red dye was then applied to the defect to highlight any remaining damage. The process was repeated until all crushed foam was removed. Conathane®¹ adhesive and PDL-1034 were applied to the repair area per standard processes, with the exception that up to three small co-located repairs were filled using PDL injected from a single syringe. Mold removal resulted in minor collateral damage at some locations which was removed by sanding the surrounding NCFI. PDL repairs were performed to 9010 requirements with the exception of an initial red dye application, which was not done prior to initial damage removal and defect depth evaluation. While PDL repair size (diameter, depth, and area) requirements were met, minor violations to 9010 repair spacing criteria were accepted by ET Project MRB action at 148 locations, LM IRT action response IRT-25.

6.2.3.3 BX-265 Spray Repairs

Non-standard BX-265 sprays were required in two areas of the LO2 tank where a high concentration of impact damage precluded PDL repair due to repair spacing and ICD considerations. One of these locations was adjacent to the ET nose cone and the other in the aft

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ogive region. The forward ogive region adjacent to the nose cone was approximately 20 inches in length and extended 300 degrees around the tank circumference. The second, in the aft ogive region, was approximately 20 inches wide by 225 inches long. In both locations, approximately 0.5 inch of NCFI was removed from the LO2 tank acreage to create a foundation for manually-sprayed BX-265. No evidence of residual damage was detected in either location after the NCFI was removed and red dye applied [ref. 23].

6.2.3.4 Additional Repairs

Minor repairs to the LO2 tank cable tray (SLA) were performed to 9010 requirements using standard repair processes.

6.2.4 Flight Rationale


ET Project flight rationale for ET-124 is based on verification by inspection, test, analysis, or similarity that repairs meet the derived requirements established in the 9010 specification. Flight performance of repairs conducted using equivalent processes and under similar circumstances offers additional confidence, especially those done to repair hail damage sustained during the STS-96 processing flow and woodpecker damage during STS-70. Performance of a stress relief groove cut in the LO2 tank acreage foam and flown on STS-91 offered some visibility into the ascent performance of NCFI with significant waviness. The debris risk change posed by the sheer volume of repairs was assessed by the SSP Systems Engineering and Integration (SE&I) organization using the Probabilistic Risk Assessment (PRA) process established after STS-107.

6.2.4.1 Test and Analysis

A number of tests and process demonstrations were conducted by the ET Project to substantiate flight rationale for ET-124 repair procedures. The key testing focused on crushed NCFI, PDL repairs, and the BX-265. Process demonstrations were required to validate the BX-265 sprays and the one-syringe / three-pour process used for the PDL repairs.

6.2.4.1.1 Crushed NCFI 24-124 Foam Testing

The objectives of the crushed NCFI 24-124 testing were to demonstrate that performance of the repaired and un-repaired crushed foam would be acceptable in expected pre-launch and flight environments. The combined environments, thermal-vacuum, and hot gas tests were meant to demonstrate that foam insulating properties would be preserved on the pad and during ascent, and that significant debris liberation would not occur in flight. Testing was conducted under conditions intended to simulate the heat rates expected in the LOX ogive area on ascent. Icing tests were intended to demonstrate that no unacceptable ice/frost buildup will occur even in foam that is crushed to the detectability limit (i.e., barely visible damage).

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Extensive crushed foam testing was conducted in conjunction with the STS-114 In-Flight Anomaly (IFA) investigation and much of this data was applicable to ET-124. The results of tests conducted to support development of STS-96 hail damage flight rationale were also available and were reviewed. Additional testing of panels with simulated hail damage was performed at the request of NESC. NCFI 24-124 panels were sprayed to a thickness representative of the high density impact damage area away from the nose cone BX-265 manual spray repair. The panels were impacted in such a manner representative of the STS-117 hail damage. The panels were inspected and repaired using the same techniques, processes and criteria planned for ET-124. Hot gas testing was then conducted to assess the potential for foam loss.


6.2.4.1.2 PDL Testing

Hot gas tests were performed for STS-70 on multiple closely-spaced PDL 1034 repairs. For ET-124, two TPS repair tests were performed to re-qualify PDL 1034 supplied by a new vendor. These were subjected to thermal vacuum and hot gas conditions.

A process demonstration for multiple PDL 1034 pours from a single syringe load was conducted at KSC and documented in TPSB SS20-613 and TPSB SS20-614. The revised process was implemented to increase overall efficiency of the repairs without sacrificing quality. The efficiency increase was desirable in order to perform repairs in a “production mode” that would support repair schedule milestones. The demonstration showed that three holes in close proximity was the limit for a one-syringe application of PDL. No dissection measurements or photographs were collected during these demonstrations. The process demonstration results are summarized in Appendix E.

6.2.4.1.3 BX-265 Manual Spray Testing

Key tests run to substantiate the ET-124 BX-265 sprays are outlined at Appendix C. Spray process demonstrations were conducted to validate the BX-265 repairs. A mockup of the ET nose cone “pencil sharpener” area was built-up at MAF and sprayed using processes and access constraints identical to those planned for the flight vehicle. The strength of the sprayed BX-265 was measured using the plug pull technique to validate the application process. Unexpected low tensile strength measurements in a few plug pulls were attributed to either an off-nominal plug pull technique or to suspected insecticide contamination. A follow-on flat panel test spray was conducted and additional tensile strength measurements were taken, tests were conducted to determine the influence of insecticide contamination.

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6.2.4.2 Flight History

6.2.4.2.1 STS-96 ET-100 Hail Damage: Debris, Ice and TPS Assessment

During on-pad processing for STS-96, ET-100 sustained over 700 instances of impact damage due to hail. Approximately one-third of those were acceptable “as-is”, one-third were repaired by blending the damage with adjacent foam, and the remaining one-third were repaired with PDL fills. All damaged areas in the LO2 tank “no ice zone” were repaired according to certified design repair criteria.

Flight rationale was presented at the STS-96 / ET-100 Pre-Launch Mission Management Team (MMT) Review on May 25, 1999 for flying ET-100 as-repaired. The rationale indicated the blended areas were returned to drawing tolerances. The sand and blended areas met all thickness and waviness requirements. PDL repairs were certified by a variety of tests and analyses including wind tunnel testing, radiant ablation tests, combined environments tests, coupon tests, and manufacturing validations. Tests of simulated hail damage were also conducted as reported in the test report ETTP-621, Hail Damage Simulation on NCFI 24-124. Stress analysis showed that the repaired NCFI 24-124 satisfied the 1.10 factor-of-safety requirement.

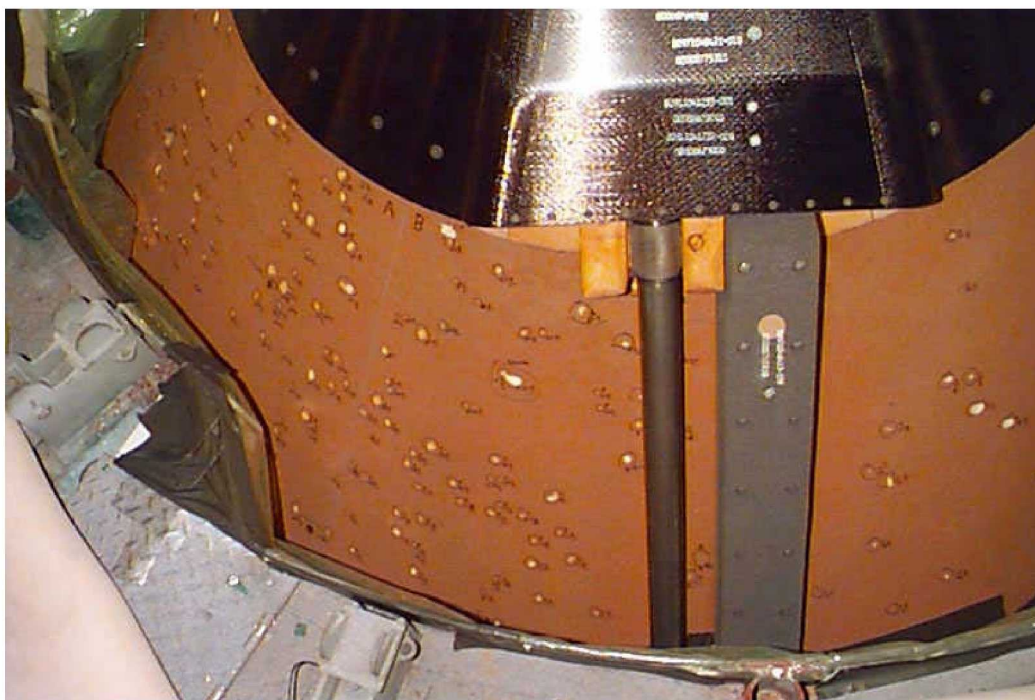



Figure 6.2-3. STS-96 ET-100 Typical Hail Damage

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Pre-Launch Inspection


Prior to launch of STS-96, a final pre-launch inspection was conducted. There was no Launch Commit Criteria (LCC), Operation and Maintenance Requirements (OMRS), or National Space Transportation System (NSTS)-08303 criteria violations. No ice, debris, or TPS problem reports were identified.

The STS-96 Ice Inspection Team report indicated that the ET in general had no NCFI acreage icing concerns and no protuberance (i.e. IFR, PAL ramp, bi-pod strut) icing conditions outside of the established database. The TPS performed nominally during cryogenic propellant loading.

The LO2 tank acreage had visible condensate but no ice or frost formations. All hail repairs were intact and exhibited no thermal shorts. No anomalies were detected on the inter-tank. The LH2 tank acreage had condensate but no ice or frost formations. After the pad was cleared for launch, the Ice Inspection Team continued to monitor the vehicle with remote cameras and infra-red radiometers. There was no ET acreage ice observed and no noticeable increase in protuberance icing was detected. The report did indicate that there was extensive surveillance of the hail damage to verify repair integrity and the absence of ice formation.



Figure 6.2-4. STS-96/ ET-100 Pre- and Post- Launch Comparison

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In-Flight Assessment

A re-configured ET intertank flown on STS-96 incorporated thousands of pin-size vent holes with 0.3 inch spacing on the ET –Y and +Y thrust panels. Significantly more debris was observed in the ET separation photography coming from the non-vented areas of the intertank than from the vented areas. The divots in both areas appeared to be shallow with no primed substrate visible. There were over 500 divots observed.

ET/Orbiter umbilical separation films were used to observe the hail damage repairs. The repair areas visible in the sunlit section appeared to be intact and in good condition per the KSC report. At the Debris Integration Group meeting on March 28, a report from the JSC SE&I Imagery Integration presented results of a study of the STS-96 (ET-100) LO2 tank repair performance after hail damage, Shuttle ascent, and ET separation [ref. 17]. The report concerned use of stereo image analysis to compare the pre-launch tank repairs with a post-separation photo of about the same region of the tank. This report observed that, post-separation, the repair areas appeared to have surfaces that were even with or slightly depressed compared to the surrounding foam surface. None of the possible depressions has measurable depth using their stereo analysis techniques (it was reported that depressions would have needed to be greater than about ½ inch deep to be measurable). The Imagery Integration team concluded that it is possible that one of the apparently depressed regions might be associated with a foam loss, but that there was no quantitative evidence to support the conclusion. The group reported that no other repairs appeared to have additional foam loss.

A report from the Image Science and Analysis Group at JSC at the same meeting also compared pre-launch imagery to on-orbit umbilical camera imagery to determine whether hail damage repairs were observed to be lost during ascent [ref. 2]. Sizes and gray-scale (brightness) comparisons were made between the pre-launch and on-orbit imagery. The report indicated no indications of change in the repair footprints, and the color of the repair areas in the on-orbit photos is reported to be significantly darker than newly exposed foam. The report concluded that there were no “significant losses” of foam repairs in the observed region of the tank.”

An additional photographic analysis was done by Dr. William Kaukler of the University of Alabama in Huntsville; performed stereographic analysis of pre-launch and on-orbit photographs (Figure 6.2-3). Dr. Kaukler investigated 17 regions that he believed to show some indication of foam recession after ascent. Only one of these regions correlated with a PDL repair (the others presumably having been sanded regions). Dr. Kaukler reported a “negative correlation” between the PDL repairs and his observation of foam recession” [ref. 12].

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Post Landing Debris Assessment

Post-landing debris impact assessment of the Orbiter indicated 160 lower surface hits of which 66 were greater than 1 inch. Boeing's post-landing report for STS-96 [ref. 16], noted that most of the damage was concentrated from the nose gear to the main landing gear wheel wells on both left and right chines as shown in Figure 6.2-5.

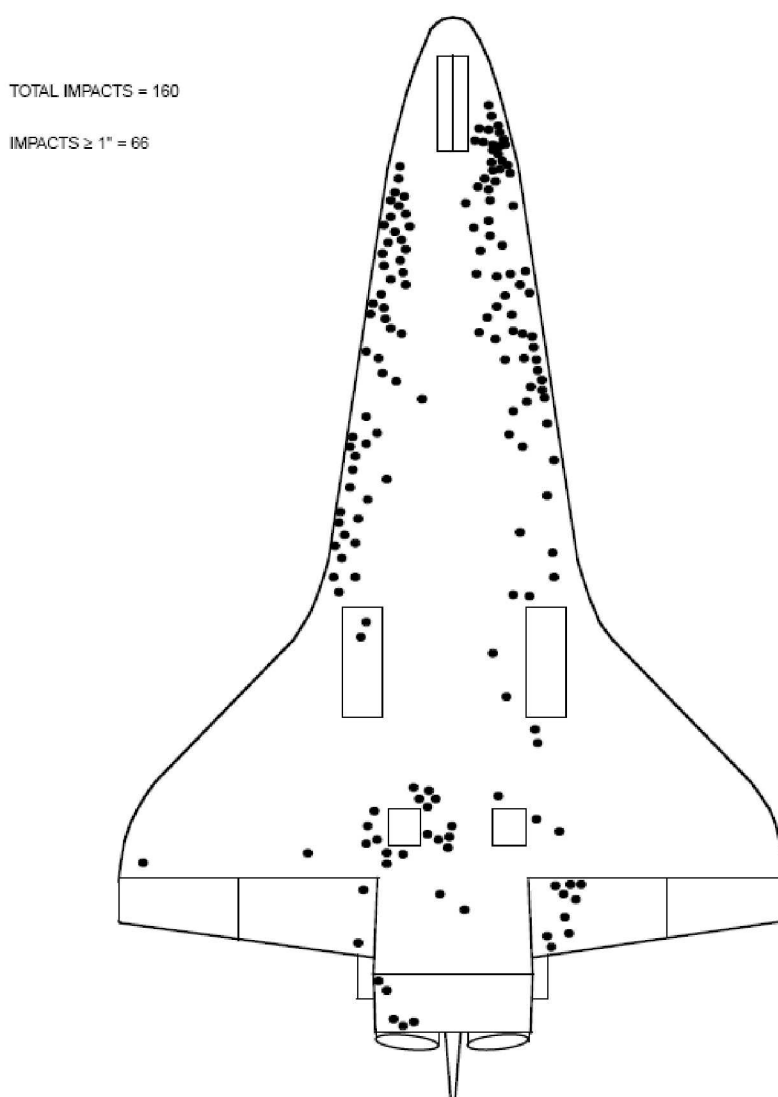



Figure 6.2-5. Lower Surface Orbiter Damage

The Boeing report also noted the outboard damage sites on the chine areas followed a similar pattern documented on other missions [ref. 16], as shown in Table 6.2-2. A higher than average NESC Request No.: NESC 07-005-E

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number of debris impacts along the chine areas was observed for STS-96. The number of impact damage sites greater than 1 inch was also higher than average, however, the depth of the damage was relatively shallow.

Table 6.2-2. Data from Boeing Report

	Lower Surface (total hits)	Lower Surface (hits > 1 inch)	Longest damage site (inches)	Deepest damage site (inches)
STS-86	100	27	7	0.4
STS-87	244	109	15	1.5
STS-89	95	38	2.8	0.2
STS-90	76	11	3	0.25
STS-91	145	45	3	0.5
STS-95	139	42	4	0.4
STS-88	80	21	4.5	0.5
STS-96	160	66	4	0.5

This period in the SSP included significant changes in the ET. The Super Lightweight Tank (SLWT) was introduced with ET-96 concurrent with an increase in “popcorning” foam losses from NCFI on the intertank. An effort was made to control this through modifications to the surface of the NCFI foam which ultimately led to the vented configuration adopted for STS-101 (ET-102). ET-100 was one of the tanks in a transitional series which incorporated design modifications to reduce these intertank foam losses and had modified venting applied to a limited area as a flight test of this technique. The number of larger than one inch diameter damage sites on the Orbiter was higher for STS-96 than for other missions with a similar intertank foam configuration; however, higher-than-normal “popcorning” foam losses were observed for ET-100. Data in Figures 6.2-5 and 6.2-6 are from [ref. 28]. This data shows “popcorn” foam loss counts from flight image analysis for ET thrust panels for STS-93, 96, 103, and 101. Higher foam loss counts are seen for ET-100.

While not conclusive, flight data analysis suggests the damage to the orbiter seen on STS-100 was caused by popcorn foam from the ET intertank and not loss of hail damage repairs.



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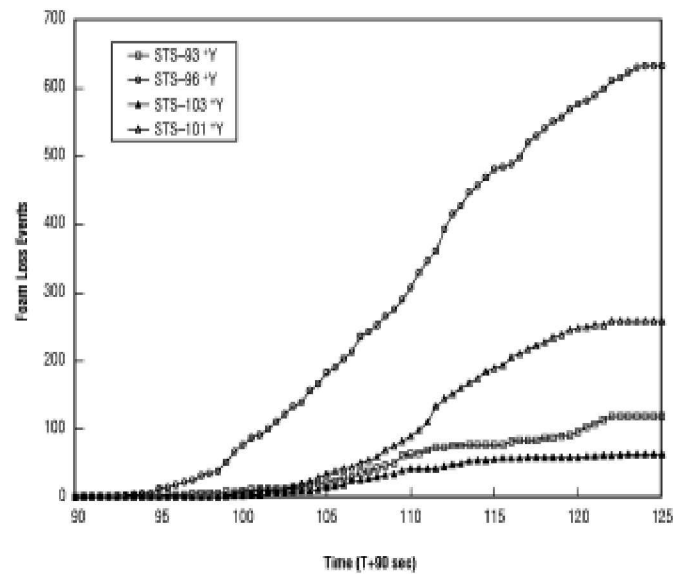


Figure 6.2-6. Foam Loss Comparisons for +Y Intertank Thrust Panels

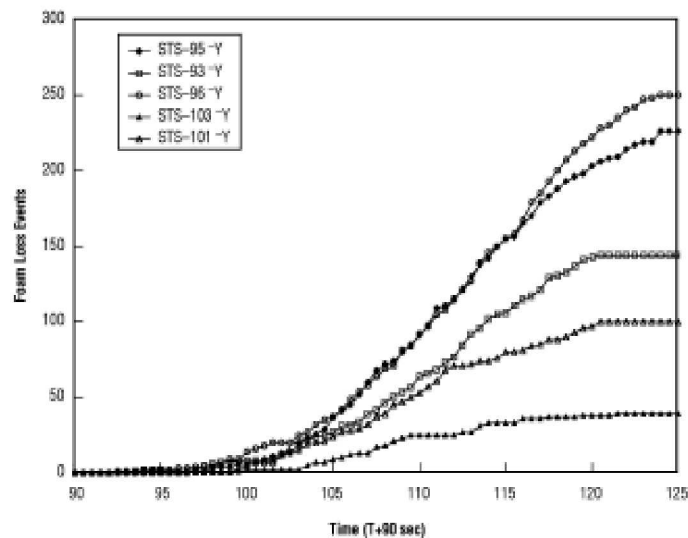



Figure 6.2-7. Foam Loss Comparisons for +Y Intertank Thrust Panels

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6.2.4.2.2 STS-70 ET-71 Woodpecker Damage: Debris, Ice and TPS Assessment

STS-70 (ET-71) was being prepared for launch in June 1995 when woodpecker damage to the ET occurred. This tank did not have the NCFI 24-124 intertank foam. The repair process on damaged areas included trim out and PDL repairs. More than 190 damage sites were reported and 167 were repaired with PDL. The remaining damage was “used as is” or sanded and blended [ref. 3]. Repairs began on June 8 and were completed by June 14, 1995.

Pre-Launch Inspection

During the pre-flight final inspection there were no LCC, OMRS, or NSTS-08303 criteria violations. There were no interim problem reports generated. The inspection team specifically checked the woodpecker damage repairs. No ice or frost formations, debonds, or material protrusions were observed.

The ET in general had no acreage or protuberance (i.e. Ice/Frost Ramp (IFR), PAL ramp, bipod strut) icing conditions outside of the established database. The LO2 tank acreage had condensate, but no ice or frost formations. The woodpecker damage repairs were intact and exhibited no thermal shorts. No acreage anomalies were detected in the intertank. There were typical ice and frost accumulations on the intertank Ground Umbilical Carrier Plate (GUCP). The LH2 tank acreage had condensate, but no ice or frost formations.

There was no further mention in the report of the time span from the final inspection through launch. It is assumed there was no additional icing observed from the remote cameras, since the inspection team summary indicated no interim problem reports were generated

In-Flight Assessment


On-orbit film and video review by KSC indicated the LH2 and LO2 tank acreage was in good condition with no visible divots or abnormal regression. No divots or TPS anomalies were observed at the woodpecker damage repair locations. The report also stated there was no indication of intertank acreage divots. The JSC Photographic Analysis Summary concurred the woodpecker repairs appeared to be intact.

Post Landing Debris Assessment

Boeing’s post-landing debris assessment indicated lower than average tile damage. There were 81 total lower surface hits with only 5 were greater than 1 inch. The damage sites appeared to be randomly distributed on the aft half of the Orbiter lower surface. There was some concentration around the LH2 ET umbilical door. However, the uniform distribution of damage sites in the chine areas, seen on STS-96, was not present on STS-70

6.2.4.2.3 STS-91 ET-96 Stress Relief Groove

The ET flown on STS-91 was the first of three tanks flown with a stress relief groove cut in the LO2 ogive acreage foam as shown in Figure 6.2-7. The stress relief groove was required to

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relieve NCFI foam induced compression loading on a LO2 ogive weld joint. The groove was approximately 14 inches wide, by 6 feet length, 1 inch deep; it was created by sanding and blending the NCFI. While the modification created significant surface waviness, flight photos showed no evidence of abnormal erosion or significant foam loss from the LO2 tank (Figure 6.2-8).

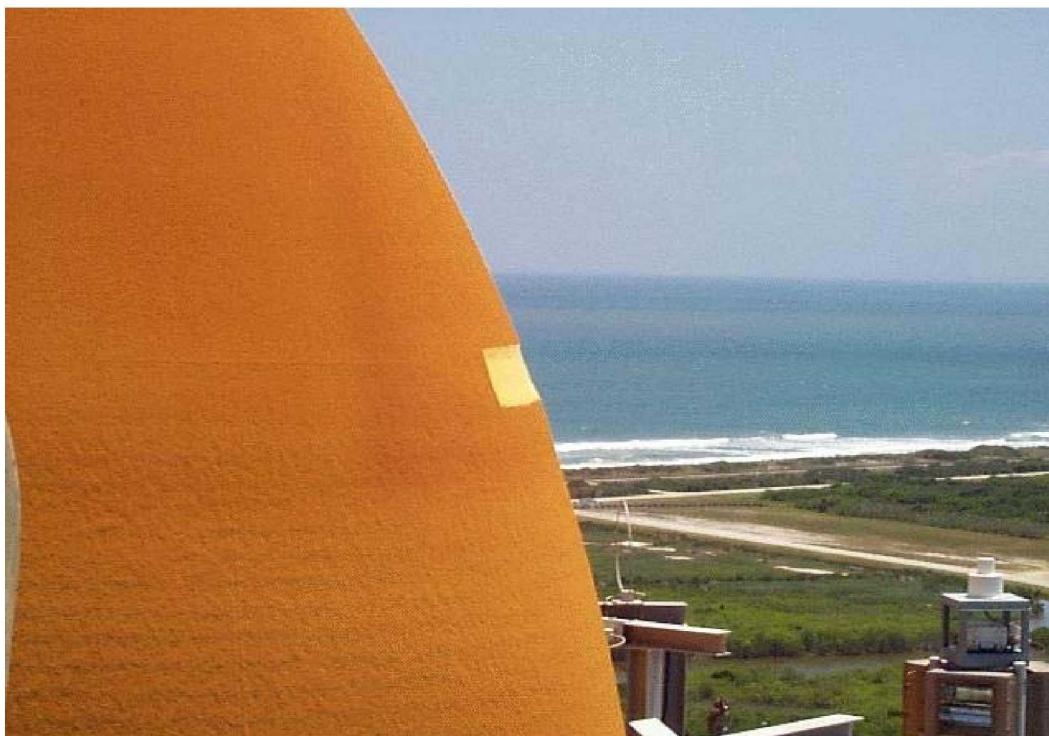



Figure 6.2-8. STS-91 LO2 Tank Stress Relief Groove

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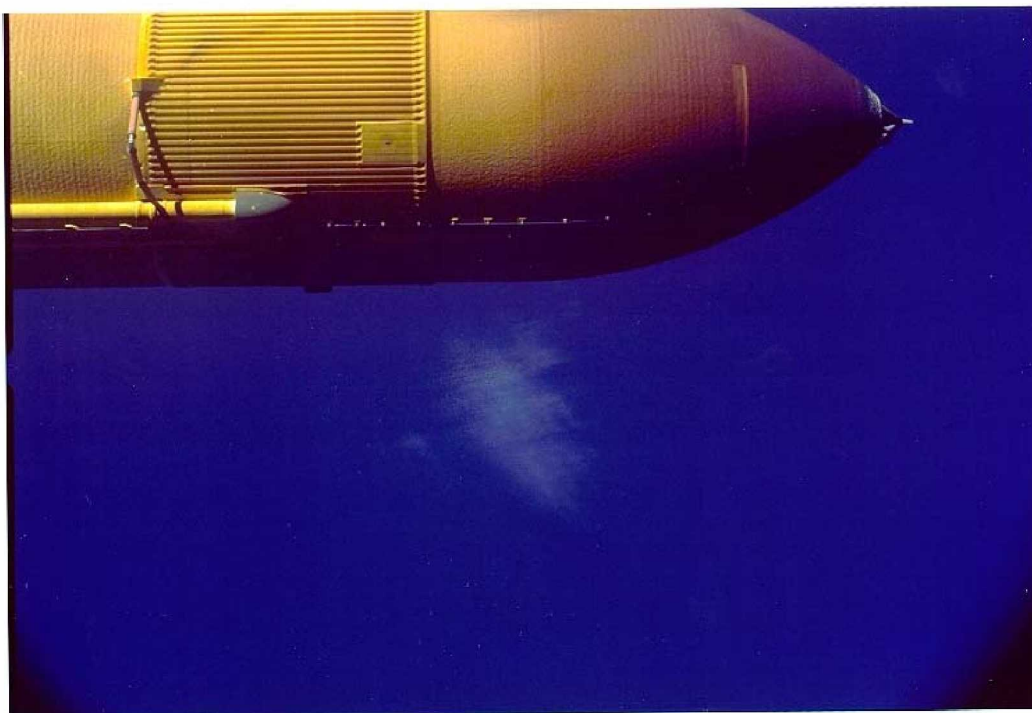



Figure 6.2-9. STS-91 Post-Separation Photo

6.2.4.2.4 Performance History of PDL-1034 Repairs

Standard PDL-1034 repairs are test-demonstrated and have been used extensively over the life of the Program with outstanding performance [ref. 24]. As discussed in the flight histories of STS-96 and STS-70, no performance issues were observed with PDL repairs used for previous hail- and woodpecker-damaged LO₂ tanks. There have been no conclusive observations of PDL repair losses from any LO₂ tank, although PDL repair losses from the LH₂ tank and intertank have been observed and were one subject of the STS-114 ET IFA investigation [ref. 15].

A number of documents were reviewed by NESC relevant to the historical performance of PDL repairs and are summarized in Table B-1 of Appendix B. The PDL Verification and Validation (V&V) data presented in these reports is limited to four sets of data gathered using similar, but non-identical, processes. Pre-STS-107 V&V data did not record voids less than 0.5 inch (reporting size limit). The post-STS-107 longeron repair data set consisted of five samples, three of which had slot defects up to 0.4 inches in diameter. The last two data sets were taken from on-tank TPS dissections and recorded cylinder defects from 0.7 inch to 0.98 inch in length and slot defects up to 0.58 inch in diameter.

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6.2.4.3 Probabilistic Risk Assessment

The large number of repairs on ET-124 represents an unquantified increase in flight risk. In an effort to estimate the risk incurred by the repairs, the Shuttle Program Systems Engineering and Integration Office (SE&I) is performing a probabilistic risk assessment for the PDL repairs on ET-124 [refs. 20, 21]. This analysis assumes that the mass of a liberated repair would be equal to the mass of PDL represented by the repair volume. Repairs greater than the deterministic limit of 0.004 lbm are considered for further analysis if they were within the $\phi = \pm 110$ degree +Z region of the tank. The conditional per-release hazard for single debris liberation is then calculated using three assumed timing distributions (uniform 35-135 seconds, following the heating rate, following the dynamic pressure) and the same debris transport model employed for previous flights. A release rate of 1/500 is assumed to arrive at a mission risk. This rate is based on the STS-121 (ET-119) flight during which one PDL repair loss was observed out of about 500 repairs on the tank and assumed typical of most missions. There is uncertainty in this estimate: ET separation imagery is not captured on all flights, and not all repairs are visible in the images that do exist. The overall flight risk from PDL repairs is sensitive to the choice of release rate; for example, if the release rate is halved the risk doubles. Initial SE&I analysis using the 1/500 rate produced an estimated maximum 1:4000 risk for repair loss from the LO2 ogive [ref. 21]. Analysis performed using a 1/100 rate produced an estimated maximum 1:800 risk.

6.2.5 NESC Participation in ET Project Assessment and Planning Meetings

The NESC Team actively participated in the ET-124 hail damage repair effort from early evaluation of the impact to completion of the repairs. Team members participated in project planning and review meetings and maintained informal communication with ET Project management and KSC, MSFC, JSC, and LMSSC personnel.

The hail damage daily engineering assessments were critical planning and reporting meetings held early in the process of recovery from the hail event. Members of the NESC Assessment Team participated in these daily teleconferences. The ET Chief Engineer Review Board (CERB) meetings were held frequently and were the forum for technical discussions of the damage assessment and repair planning. Those teleconferences were used to discuss repair approaches and their validation. NESC team members participated in these meetings, especially when key decision points were being proposed. The NESC team was represented in numerous Technical Interchange Meetings (TIMs) scheduled when a significant milestone or decision point was being approached and a significant amount of data was available for review. NESC Assessment Team members participated in the weekly Shuttle Program Requirements Control Board (PRCB) meetings during which the ET project routinely discussed status and progress in the ET-124 recovery effort. Additionally, the NESC Assessment Team members engaged in numerous informal meetings with ET project representatives and with ET and Shuttle Propulsion Chief and Deputy Chief Engineers. The NESC Assessment Team Lead also participated as a member of an Independent Review Team (IRT) chartered by the ET Project to review and comment on damage

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repair efforts prior to rollout from the Vehicle Assembly Building (VAB). Lockheed-Martin (LM) responses to actions levied by the IRT.

7.0 Data Analysis

Appendix C contains a list of tests, analyses and miscellaneous documents relevant to the ET-124 repair that were reviewed by NESC.

7.1 Inspection and Disposition of Damage


Damage inspections were performed by teams of experienced inspectors from engineering and S&MA and included both MAF and KSC personnel. Despite the extent and thoroughness of those inspections, the potential remains that some crushed foam may have escaped detection. Data collected during the STS-114 IFA investigation indicated that crushing up to 15 percent of thickness cannot be reliably detected by visual inspection. Since red dye was not applied to all defects as a visual indicator, especially foam in areas where damage was superficial and defects were dispositioned for use as-is or where sand-and-blend repairs were performed (see section 6.2.3.1), the possibility that some crushed foam remains is increased.

The potential for undetected damage to the tank shell is minimal. Any hail impact sufficient to cause structural damage to the tank would have left visible damage on foam as well. No pressure vessel substrate was exposed by any of the impacts.

Inspection of composite components (nose cone, gaseous hydrogen (GH₂) pressurization line fairing, and intertank access door) revealed no anomalies. NESC reviewed and concurs with the inspection assessment (Appendix J).

7.2 Crushed Foam

The body of crushed foam test data produced in support of the STS-114 IFA is extensive, and is supplemented by hail damage simulation test data gathered during STS-96. Panels with foam crushed at various levels were subjected to thermal-vacuum and hot gas testing during the IFA work and liberation of debris with a mass in excess of the deterministic limit (0.004 lbm) observed only when large-diameter (3-4 inches) indenters were used to crush the foam to approximately 20 percent. Crushed foam debris liberated during hot gas testing was observed to fragment into small pieces immediately on release [refs. 13, 19]. Foam at 51 damage sites on ET-124 was treated with red dye and removed incrementally to assess damage depth. LO₂ NCFI crushing did not extend beyond about 0.2 inch of the defect bottom, and ET intertank crushing was limited to a depth of about 0.1 inch of the defect [ref. 1]. Data from dissection of STS-96 test panels is consistent with these observations; however, since the STS-96 simulations do not

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envelope the STS-117 hail event due to significant differences in magnitude, rate, and cross-sectional area over which energy was dispersed in those test articles, NESC recommended additional tests be conducted on panels designed to simulate the STS-117 damage. These tests showed a linear relationship between energy of impact and depth of TPS damage consistent with the STS-96 results, with the bulk of the crushed foam found within about 0.2 inch of the defect bottom [refs. 5, 24]. Hot gas tests were conducted on un-repaired NCFI panels subjected to STS-117 simulated damage (both static and dynamic) and no significant debris release was observed [ref. 8]. Recession rates for these panels were in-family.

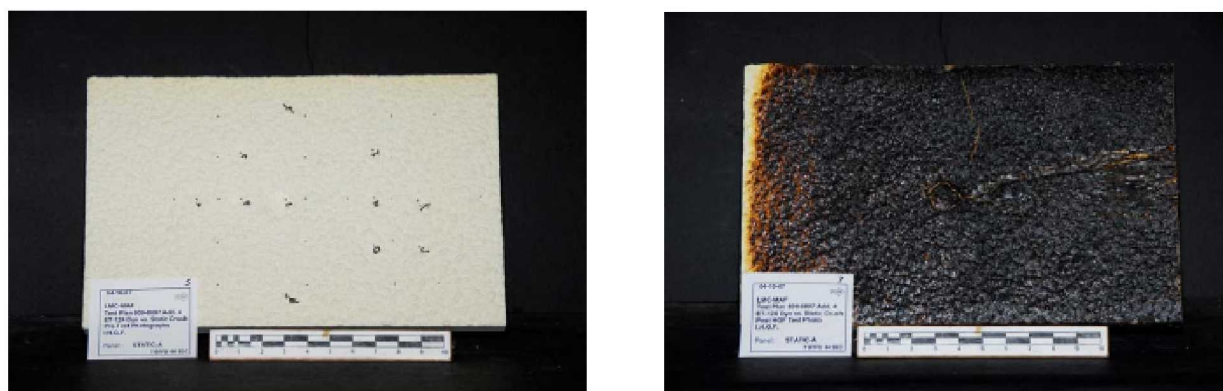



Figure 7.2-1. Hot Gas Test of NCFI Panel Subjected to Static Loads Simulating STS-117
[ref. 8]

On the basis of these tests, NESC concurs that significant debris release or accelerated TPS recession due to residual crushed foam is unlikely.

Surface and Interstitial Ice

The potential for ice to form on or in areas of residual crushed foam was assessed. Results of multiple cryogenic cycle and thermal vacuum tests performed on an NCFI panel with “barely detectible” crushed foam (crush level of approximately 15 percent) were reviewed. No ice formed during any of the 9-hour cryogenic cycles at average ambient temperatures of 62 deg F and 93 percent relative humidity. No debris in excess of the deterministic level was liberated in the subsequent thermal-vacuum test [ref. 6]. The test setup and conditions were conservative and bracket conditions expected at KSC for a June or July launch.

If the outer surface of the NCFI is at 90 deg F and the inner surface is at -297 deg F (LO2 cryogenic temperature), the temperature will be 32 deg F, 20 percent of the way into the foam thickness. That is, for 1 inch of foam, the 32 deg F isotherm will be 0.20 inch below the surface. The minimum thickness of foam remaining in the sand and blend repairs is 0.65 inch, so freezing


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temperatures at those locations can occur 0.13 inch below the surface. If ambient temperatures are lower, sub-freezing temperatures can be expected even closer to (or the same as) the NCFI surface temperature. In the test series referenced earlier, temperatures as low as 30 deg F were detected at the surface 6 hours into cryogenic chilldown. The implication is that sub-freezing temperatures can be expected within a region of undetected crushed foam regardless of ambient temperature, so the possibility that ice may form in a void created by damaged cell walls internal to a region of crushed foam (interstitial ice) cannot be dismissed on the basis of temperature alone.

Data collected during development of NESC hydrophobic coatings offers some insight into the mass of water that can be expected to accumulate in undamaged NCFI (Appendix H). Absent a communication path from the foam interior to the surface, crushed NCFI can be expected to contain a similar amount of liquid water. One inch core samples taken from freshly sprayed and 15-month weathered NCFI panels contained a maximum of 0.48 to 1.48 grams of water, respectively, within 0.25 inch of the NCFI surface (Appendix H, pg 8-9). Hail-damaged crush sites seen on ET-124 were on the order of an inch in diameter and, as noted previously, had damage typically extending no more than 0.2 inch beneath the surface. The amount of water contained in the 1 inch x 0.25 inch samples tested thus offers a reasonable estimate of the release mass that can be expected if all the water in a damage site was frozen and liberated as a single piece of debris.

Water accumulation significantly greater than the values above is unlikely, even if a communication path from the surface to the interior of a crushed foam region does exist. Air trapped in the cavity will prevent entry of liquid water unless a vent path is also present, and surface tension of the liquid will inhibit flow. If liquid water does find its way into a cavity from the NCFI surface, the increased thermal conductivity would tend to warm the deeper layers and reduce the likelihood ice will form. Cavity volume would be limited by the size of the damaged area. Again, samples collected from ET-124 and in conjunction with STS-96 and STS-117 damage simulations suggest crushed areas on the order of an inch in diameter by no more than 0.25 inch deep are to be expected. The presence of undetected large-scale crushed areas in the ET-124 tank acreage is unlikely, given the extensive inspections performed after the hail event.

Two mechanisms exist that could precipitate ice debris liberation from a region of crushed foam: void-delta pressure (V-dP) and aerodynamic heating / erosion. Neither provides a likely mechanism for liberation of surface or interstitial ice in crushed foam, even if such ice were to form. The V-dP mechanism would require presence of a void in the acreage foam adjacent to the ice, formed either during application of machine-sprayed NCFI or as cell walls were collapsed during crushing of the foam. Machine-sprayed NCFI has a low incidence of void entrapment, and the probability that multiple, disconnected voids would form in crushed foam oriented in such a way that one would produce ice while the other did not is remote. Aerodynamic heating /

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erosion would ablate the material from outside in and extensive hot gas testing indicates it does not typically produce debris in excess of the 0.004 lbm deterministic limit.

At this time, ambient temperature conditions on day of launch are expected to be much higher than the conditions successfully test demonstrated for known crushed foam conditions. Rain would increase heat transfer to the foam surface that would decrease the likelihood of icing. In addition, multiple day of launch inspections using visual, IR and SURFICE techniques are planned to ensure to acceptable launch conditions.

Given the above rationale, NESC concurs that surface or interstitial ice is unlikely to form in the vicinity of any residual crushed foam on ET-124 and the debris risk posed by such is remote.

7.3 Repair Processes

Standard repair processes appear adequate with procedures providing sufficient level of detail to minimize the potential for human errors. All repair processes applied to ET-124 have been validated by test. Technicians performing repairs were trained and certified to perform the work. The Kennedy Space Center (KSC) workforce received safety classroom training and on-the-job task-specific training. ET foam repair certifications (Critical Skill Certification CSR 889, "ET Foam Application for Repair") did not include dissection and analysis of PDL sample pours. Only experienced MAF technicians performed non-standard repairs.


Red dye was used as a damage indicator during inspections and in conjunction with all the repair procedures employed on the tank. Effectiveness of the dye as an indicator was demonstrated by test during the STS-114 IFA investigation.

7.3.1 Sand and Blend Repairs

In an attempt to minimize the removal of undamaged NCFI from ET-124 and also limit the number of PDL repairs required, minimum foam thickness criteria were reassessed and new sand and blend contours were developed and verified during the hail damage recovery effort. Wall angles of the blends are steeper than those that would have resulted had the original aerodynamically-derived blending requirements required by 9010 been applied and many of the blends are deeper than the drawing-specified minimum foam thickness. NESC reviewed the test and analysis that provides the rationale for revisions to the drawing requirements and 9010 criteria.

7.3.1.1 NESC Analysis of Waviness Criteria

During the development of the Space Shuttle, an ET outer mold line surface waviness criteria was defined by the Shuttle thermal community so that the manufacturing team would have a reasonable guideline as to how smooth the ET foam surface needed to be. The original spray-on-foam insulation (SOFI) equipment produced a corrugated, spiral pattern that would increase the

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local aerodynamic heating, at the top of the corrugations, relative to an “undisturbed” flat plate value that was determined from smooth wind tunnel models. The original waviness criterion was sized so that the local heating, on the LO2 tank ogive, would not exceed 1.3 times the corresponding smooth surface value. The corresponding “wave” amplitude and length for the ET ogive and intertank are specified in Martin Marietta Corporation (MMC) drawing 80971118408. The actual dimensions vary with position along the ogive, with the smallest wavelength and amplitude at $X_t=371$ being 3 inches and 0.18 inch, respectively.

Unfortunately, a similar criteria for cavity dimensions has never been incorporated into the ET drawing system, thus any cavity type feature has historically been treated as if it was a surface wave even though the local flow physics of the two features is very different. The diameter of the cavity, at the SOFI outer surface was being used as the wavelength, and the depth of the cavity as the wave amplitude. Any cavity that did not meet the aerodynamic waviness criteria was repaired per the directions in MMC drawing 80901019010, which requires that the surface “smoothness” meet the aerodynamic waviness criteria.

The large number of hail damage sites, on ET-124, brought this issue to the SSP Thermal Panel several times during March of 2007. During the discussions, Marshall Space Flight Center (MSFC) Engineering noted that cavity heating test data had been developed and compared it to the literature after the STS-96 hail damage event. This work was presented to the SSP Thermal Panel on March 15, 2007 and a recommendation made that the “aerodynamic waviness” criteria not be used to size the cavity repairs. Doing so would cause good NCFI foam to be removed unnecessarily as cavities were enlarged to meet the aerodynamic waviness criteria. It was further recommended that the cavity walls be sloped to minimize the local heating to the downstream wall. The SSP Thermal Panel and NESC concurred with these recommendations. MSFC Engineering and the ET Project developed and implemented a revised cavity repair specification for the Sand and Blend and Use As Repaired (USR) or Use As Inspected (USI) repairs.

Supporting thermal analyses are documented in two SSP Thermal Panel presentations, one by Michelle Guillot of Lockheed Martin, and the other by Tibor Lok, a USA consultant and IRT-24 demonstrated that the NCFI bond line temperature was a strong function of the internal LO2 ullage temperature and only a weak function of the external aerodynamic heating. Thus, even large changes to the external heat transfer rate, such as a factor of two or three, only cause modest increases to the maximum bond line temperature which occurs just before Space Shuttle Main Engine (SSME) shut down, well after peak aerodynamic heating. Panels configured with representative rounded-edge and 0.5 inch sanded-wall-angle sand and blend repairs were subjected to hot gas testing on April 14, 2007 [ref. 7]. Results demonstrated acceptable recession rates and no significant debris liberation.

NESC concurs, on the basis of these tests and analyses, that the modified waviness criteria developed for ET-124 are acceptable for flight and the shape of the sand and blend repairs should

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be optimized to minimize ice formation prior to launch, instead of only minimizing ascent heating.



Figure 7.3-1. Hot Gas Test of NCFI Panel Containing Multiple Steep-Wall Sand and Blend Repairs [ref. 7]

7.3.1.2 NESC Modified Sand and Blend Criteria and Minimum Foam Thickness

ET Project developed an option to perform deeper than normal sand and blend (S&B) repairs, i.e., repairs that would violate the minimum NCFI foam thickness required by the external tank drawings. The minimum NCFI thickness required to prevent external ice formation on the oxygen tank while ensuring an 85 percent launch probability between May and October was first established. The Program's 30-year KSC weather data base was used as input to an ice simulation program and the NCFI thicknesses in the no-ice and limited icing zones were adjusted until the 85 percent criterion was met. This effort resulted in minimum foam thicknesses of 0.8 inch in the no-ice zone and 0.6 inch in the limited ice zone vs. the established drawing minima of 1.0 inch.

The second step in this effort was to devise a method of sorting the hail damage locations into S&B and PDL repair. That is, to identify the icing potential of each prospective S&B repair and to repair with PDL those that might ice. To enable this sorting, ET Project devised an icing test in a natural convection chamber. A box fan was included in the test to allow for some forced convection. Liquid nitrogen-backed foamed panels with cavities of different depths and shapes were tested to identify the icing limits. The results were used to sort the repairs into PDL and S&B, resulting in 26 suggested PDL repairs and 301 S&B repairs. Three repairs that did not meet the sort criteria were re-designated as PDL due to concerns about an increased icing risk at these locations and depths.



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Figure 7.3-2. Sand and Blend Criteria Icing Test [ref.10]

NESC investigation of the historic weather at KSC showed that the 85 percent cutoff coincided with wind speeds that would cause the heat transfer on the LO2 ogive to be dominated by forced convection; as a consequence, there was an issue with directly using the results of a natural convection test with limited forced convection to assess the potential for S&B icing. NESC performed a physics-based non-dimensionalization of the icing potential to allow a relative assessment of the S&B icing potential from all the repair sites (Appendix F). The analysis showed that the three repair sites that had been re-designated for PDL did indeed have icing potential that exceeded other S&B sites, thus confirming the ET Project selection. The analysis also identified 11 other repair sites that had been selected for S&B that had icing potential which exceeded that of sites that had already been designated for PDL repair. NESC recommended these sites be repaired with PDL, and ET Project accepted the recommendation. Because the tests performed to establish; the PDL versus S&B repair criteria were not fully representative of the launch pad heat transfer physics, the possibility remained that launch probability due to icing could be substantially less than 85 percent. To address this concern, NESC performed a sensitivity analysis using the 30-year KSC weather set and demonstrated that, even if the physics used to set the cutoff was off by a factor of two, the probability that day-of-launch icing would not exceed Launch Commit Criteria (LCC) requirements still exceeded 55 percent. This assessment is detailed in (Appendix G).

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7.3.2 PDL Repairs

Over 900 PDL repairs were made on the ET LO2 tank, which is approximately an order of magnitude more than normal. In general, the specified PDL repair density limits (repairs per square foot and distance between repairs) have been test-validated and demonstrated to have no effect on NCFI integrity.



Figure 7.3-3. STS-70 Multiple PDL Repair Test Panel [ref. 3]

PDL material used on ET-124 had to be requalified due to a vendor change. Testing done to support the requalification also demonstrates acceptable performance of multiple PDL and S&B repairs in an environment similar to that expected on the LO2 tank at ascent [ref. 5].

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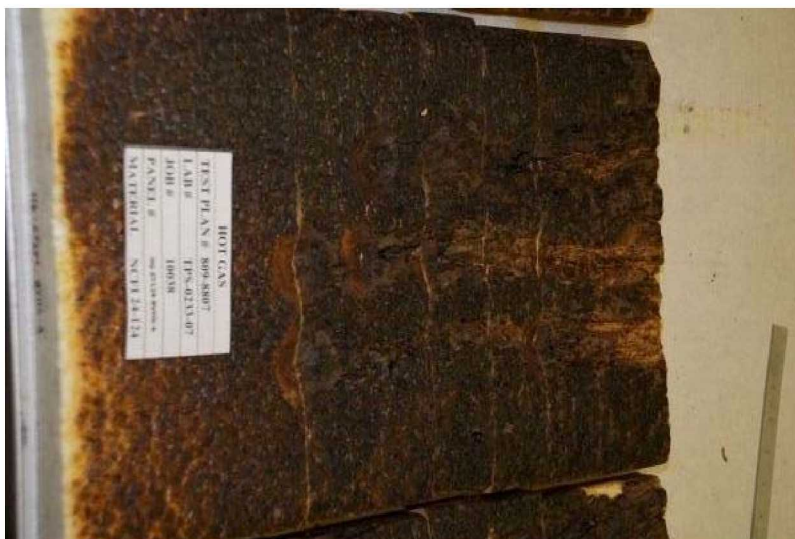



Figure 7.3-4. Hot Gas Test of PDL Repair Panel Containing Multiple Repairs [ref. 3]

7.3.2.1 NESC Human Factors Assessment of PDL Application Processes

The NESC Human Factors (HF) team reviewed procedures and working conditions prior to execution of PDL repairs on ET-124. The team visited the VAB work area, observed a damaged-foam removal demonstration and a procedure development “table top” review, and interviewed engineers and technicians involved in the work. The HF team did not make any direct observations of repairs in-progress on the tank or on high-fidelity mockups.

Procedures incorporated relevant input from all major stakeholders including technicians, engineering, and Quality Control (QC) representatives from the United Space Alliance (USA), NASA Engineering from KSC and MSFC, and Lockheed Martin, MAF. Work steps included appropriate inspection points and were written in accordance with standing procedures, requirements, and standards. The PDL repair processes varied slightly from those implemented in the past at MAF and KSC. In order to complete the number of repairs required in a reasonable amount of time, KSC adopted an “assembly line” process wherein defects were addressed in parallel instead of individually; i.e., rather than fully repair one defect at a time, technicians performed surface preparation of all defects, applied Conathane® to all defects, installed molds, poured PDL and allowed it to cure, then removed all the molds and performed final trimming. In another change from the normal process, a single charge of uncured PDL was used to fill as many as three separate defects. These changes allowed for significant gains in processing efficiency. The three pour procedure was successfully demonstrated prior to implementation. The NESC did note that while a maximum allowable delay before pouring PDL at a given

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temperature is specified, the procedures did not include verification steps to ensure this pour time was not exceeded and recommended quality inspector timing of multiple PDL pours from a single syringe to the procedure development team. The team also recommended that red dye application procedures be strengthened with specific work steps in lieu of notes. These recommendations were subsequently implemented.



Figure 7.3-5. ET-124 Access and Lighting in the VAB



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Figure 7.3-6. ET-124 Nose Cone Area Access

Training, work area access, and lighting were reviewed. The PDL repair certification / re-certification procedures used at KSC and MAF are slightly different. Most notably, the KSC training procedures do not include steps for dissection and analysis of PDL repairs, and the test panels used for KSC training are not made with NCFI foam. While access to the work area was adequate, NESC noted the lighting in the LOX ogive work area was insufficient for some tasks such as inspection of Conathane® application and identification of damaged foam prior to red dye application. NESC recommended improvements to lighting in the work areas, and that recommendation was accepted and implemented.

The Project was diligent in ensuring all known critical parameters were controlled. PDL repairs were not subjected to detailed evaluation to ascertain what effects minor process variations may have on internal void size or distribution. The existing body of PDL repair void data is summarized in Appendix B, Table B-1 and assumed applicable to the repairs done on ET-124, though no recorded data exists to validate this assumption. While the bulk of the repairs done at MAF are performed with the tank horizontal, all ET-124 repairs were done with the tank vertical. As the data in table B-1 indicates, this increases the potential for void formation. Process repair demonstrations were conducted on BX-265 panels to validate the three pour / one syringe technique, but the repair samples were not subjected to controlled dissection and no void size or distribution data was recorded documented in KSC TPSB SS20-613 and TPSB SS20-614,


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(Appendix E). Approximately 32 repairs were removed from the tank to address a concern relating to the underlying Conathane® application but again, no sub-surface void data was collected as the repairs were removed. The on-tank dataset is thus limited to verbal “no voids noted” reports gathered in conjunction with the validation tests and repair removals.

Despite a variety of process controls, the sheer number of repairs increased the probability that process escapes or creep could occur. Manually sprayed foam applications are normally validated by lead-in / lead-out tests done on mock-ups, and NESC recommended this process be extended to the hail damage repairs through routine collection of sample data as those repairs were performed. Ideally, sample repairs would have been made on NCFI or BX-265 panels off the tank at the beginning and end of every processing shift and those repairs dissected to monitor sub-surface void size and distribution. This would have yielded a body of data to validate the void distributions assumed for the subsequent PRA and would have provided visibility to ensure no process creep was occurring as the repairs were completed. The Shuttle Program did not implement this recommendation, and no in-process data was collected. The Program proposed gathering additional data from PDL test pours after all on-tank PDL repairs were complete. Such data would not have been sufficient to address the process creep concern, however, and given the unknown effects minor process variations may have on internal void size and distribution may have led to erroneous conclusions. Consequently, NESC concurred with not gathering PDL test pour data after the on-tank PDL repairs were complete.



Figure 7.3-7. Sectioned PDL Repair Following Hot Gas Test [ref. 5]

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Although no on-tank void distribution data was collected, it is reasonable to assume the quality of the ET-124 repairs does not differ significantly from those applied to other tanks, with most repairs similar to the one depicted in figure 7.3-7. PDL repair application is a multi-step process, and as noted earlier the Project was diligent in ensuring that controls were placed on each step in the process. Previous dissection data indicates that internal voids are expected in PDL applications (see Section 6.2.4.2.4). The bulk of the repairs are small (approximately 1 inch in diameter by 0.5 inch deep) and any extremely large voids would likely have breached the repair surface and failed inspection. NESC concurs with the use of previously-collected MAF data for the PRA with the recognition that lack of specific knowledge regarding the size and location of sub-surface voids in ET-124 repairs adds additional uncertainty to the results.


7.3.2.2 PDL Repair Process Control Issues

The current Shuttle PRACA definitions of process escapes and catches are [ref.18]:

- “A process escape is defined as any problem identified after it should have been detected during normal processing. Process escapes include problems found during surveillance sampling, inspection (including random), or audit after final closeout, or final flight configuration verification.”
- “A problem can be defined as a process catch if it is identified during normal processing (departing from procedure), inspection, or surveillance sampling prior to final closeout or during testing.”

Several process control issues (catches and escapes) occurred during ET-124 repairs, including a Conathane® application issue, collateral damage during mold removals, and a PDL maximum hardness verification issue. These process issues provided an indicator that existing process controls were not completely effective, and they raised questions about additional process issues that may have occurred but were not identified as either process catches or escapes.

The PDL repair rework rate resulting from these process control issues exceeded 30 percent (32 re-repairs due to the Conathane® application issue, 88 missed Shore A hardness tests, approximately 300 sand and blend repairs due to collateral damage incurred during mold removals, and several post-application repair discrepancies). Rework rates from comparable industry processes can be expected to be at least an order of magnitude lower than the PDL repair rework rate. For comparison, six-sigma process performance corresponds to 3.4 defects per million units, or a defect rate of 0.00034 percent. In statistical process control, the process boundaries used to support calculations of process capability (C_p indices) usually do not include post-process inspections, so process catches and process escapes do not affect measures of process capability.

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Conathane® Application Process Issue

KSC OP-300 Step 16 states: “Conathane® is to be applied to a thickness of 0.003 to 0.010 inches, measured with 1 each wet film gage.” However, a note in the procedure also stated: “Adhesive thickness shall be determined using a wet film gage, when necessary. In the event that an area is inaccessible to these instruments, a visual verification of thin, uniform coating shall satisfy the thickness requirement.” The wet film gage is required for all thickness verifications. The procedural discrepancy with the requirement was identified by USA Quality Control, and the corrective action was a permanent deviation (redline change) to the operating procedure that removed the visual verification option. Approximately 32 discrepant repairs were removed and those ET locations were re-repaired.

Post-Application Discrepancies


Several discrepancies were noted during post-application inspection of repairs, including some PDL underfills and surface voids. The discrepant repairs were removed from the tank and replaced.

Collateral Damage During Mold Removal

Minor unexpected damage to surrounding NCFI occurred when PDL pour molds were removed. The “production line” repair environment left molds installed on the tank for a longer period of time than is typical when individual repairs are made. As a consequence, the sealant used to attach the molds lifted some NCFI rind as it was removed. The damage was removed by light sanding.

PDL Maximum Hardness Verification Process Issues

MAF work instructions contain maximum hardness verification for all PDL repairs per acceptance criteria. Shore A hardness tests are performed to ensure that the hard surfaces of the PDL repairs have been sanded/removed. This test was typically not performed on sanded foam at KSC during OP-300. Lockheed Martin Engineering identified the omission as a process issue following an in-depth comparison of KSC and MAF procedures, and the paperwork was changed to have Shore A hardness tests performed on all PDL applications on the LO2 tank. Hardness tests were also to be performed for accessible PDL repairs on the LH2 tank. A Material Review (MR) action was initiated for all inaccessible locations on the LH2 tank. During post-test paper reviews, it was discovered that 88 PDL applications from the initial group of LO2 tank repairs did not have Shore A hardness tests performed. KSC Engineering wrote an operation to perform the hardness test on the initial 88 repairs, to date this work has not been completed and the Project is working towards acceptance of a "use as is" MR.

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7.3.2.3 PDL Process Improvements

ET-124 repairs benefited from lessons learned during the STS-114 IFA investigation. Multiple red dye applications were made to ensure all crushed foam was removed from PDL repair locations, thus minimizing the potential for entrapment of a void in crushed foam beneath a repair. ET-124 repairs were of a relatively simple geometry, with NCFI excavated from the tank using Dotco®² cutters similar to those pictured in Figure 7.3-8. These cutters excavate a circular hole with a square-edged bottom identical to the cutter profile. The NESC Human Factors team noted that application of a radius to the bottom shoulder of the cutting blades would produce a bathtub shaped hole less likely to trap voids during PDL backfill. A Dotco® tool guide developed by technicians for use as a shop aid in excavating NCFI foam illustrates a creative process improvement to increase repair reliability. Unfortunately, the Dotco® tool guide was not fielded in time to support the ET-124 repairs. Other such improvements could be implemented to minimize the size and number of voids produced by the repair process.

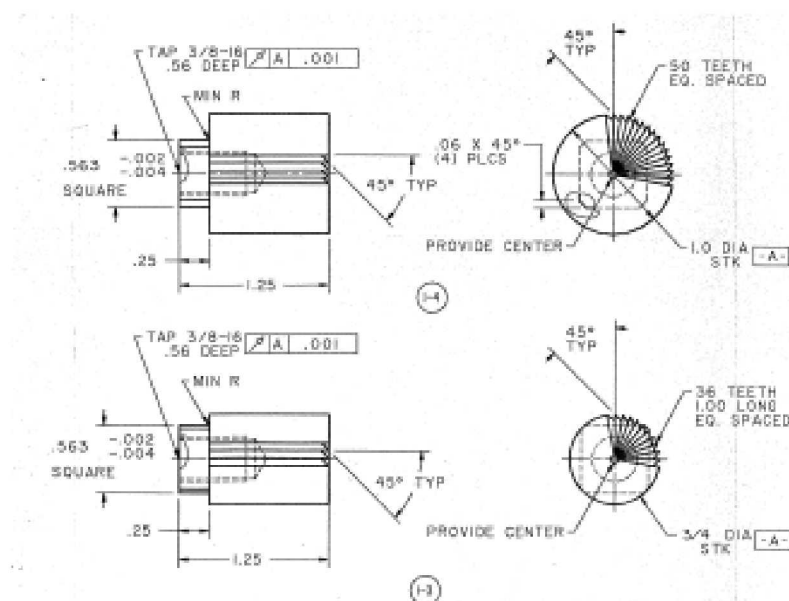



Figure 7.3-8. Typical Dotco Cutter Profiles [ref. 22]

7.3.2.4 PDL Repair Summary

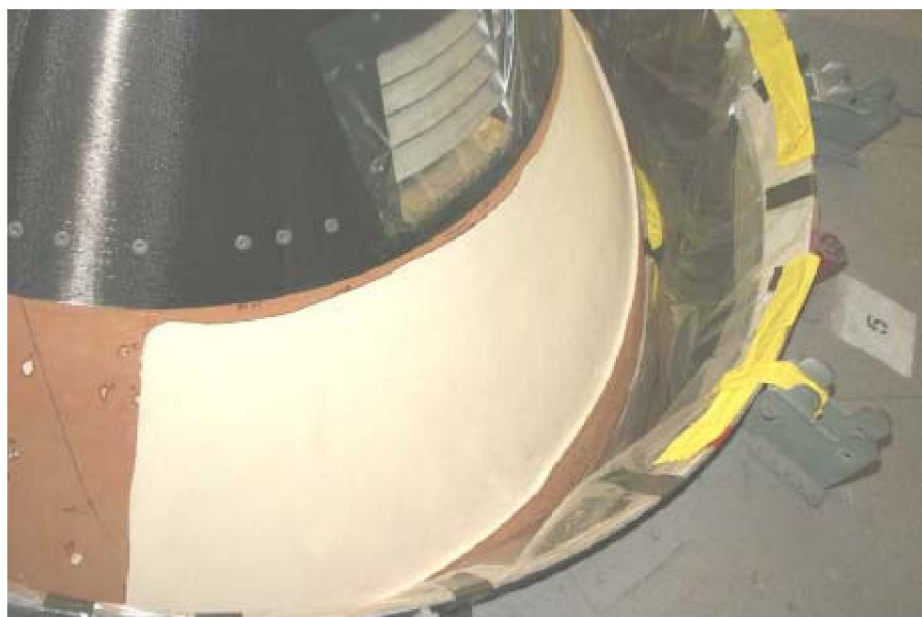
PDL repairs have been routinely implemented throughout the life of the Shuttle Program and are supported by test and analysis. Flight history, though necessarily limited due to tank visibility and photographic resolution issues, has shown few repair losses over the course of the Program; indeed, no losses from the LOX tank have been positively identified. PDL application

² Is a registered trademark of Dotco, Inc. Corporation Ohio Hicksville Ohio
NESC Request No.: NESC 07-005-E

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procedures developed at KSC appeared adequate and all steps in the repair process were protected by process controls. Although the void distribution of on-tank repairs is assumed identical to that observed in repairs done at MAF, no data exists to substantiate this assumption and no in-process data was collected as a control against process creep. Such data would strengthen flight rationale, but NESC concurs with flight on the strength of the process controls known to be in place when the repairs were implemented.

7.3.3 BX-265 Repair Sprays



**Figure 7.3-9. Partial View of ET-124 Pencil Sharpener BX-265
Spray Repair Area [ref. 24]**

The BX-265 spray process was validated with a demonstration spray performed on an ET nose cone mockup [ref. 11]. Post-test dissections revealed no voids. NESC reviewed the plug-pull data collected in conjunction with the test and with a subsequent flat-panel spray and concurs with ET Project that the low values observed in the demonstration samples likely occurred due to contamination of the test article surface. Data collected from lead-in / lead-out sprays performed when the BX-265 repair was made to the flight article were well within spec and adequate to demonstrate acceptable material properties. The sprays were applied to the LO2 tank by experienced MAF technicians using identical techniques and equipment. Adhesion of the BX-265 material to the Conathane® layer has been demonstrated in previous tests conducted to validate the PAL ramp repair process and confirmed through hot gas tests performed for ET-124 [ref. 11]. These tests demonstrated BX-265-over-NCFI performance in environments similar to those expected in the ET-124 LO2 ogive area on ascent. No foam liberation in excess of the

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0.004 lbm deterministic limit was noted, and no significant erosion occurred. This testing envelopes conditions expected in the aft portion of the LO2 tank. NESC reviewed the thermal analysis performed by ET Project to demonstrate no significant increase in bondline temperature would occur at the BX-265 to NCFI interface and concurs with the assertion that the 300 degrees F temperature limit will not be violated [ref. 24].

BX265 and NCFI Coefficient of Thermal Expansion (CTE) Mismatch


At -320 deg F (LO2 substrate temperatures), aluminum has a CTE of -0.0031, NCFI 24-124 a CTE of -0.0166, and BX-265 a CTE of -0.01812 [ref. 14]. The difference of about 10 percent between BX-265 and NCFI is not sufficient to impart stress in the TPS beyond the limits of material capability and does not pose a concern for in-flight debris liberation. The 0.5 inch layer of BX-265 will not insulate the NCFI sufficiently to impart significant internal stress in the material, and thermal cracking of the kind seen in the PAL and ice / frost ramp area is improbable. The underlying structure in the ogive areas of interest is stable and will not impart undue loads in the TPS.

On the basis of these tests and analyses, NESC concurs that the debris release above deterministic limits or accelerated TPS recession in the areas of the BX-265 spray repairs is unlikely.

7.4 Flight Risk Assessment

The Program's PRA approach is identical to that of previous missions and suffers from the same limitations, primarily the uncertainties inherent in estimates of debris mass, debris release timing, transport, and orbiter impact damage. As noted in previous NESC assessments, the PRA should not be used as a discrete estimate of flight risk but is suitable only for assessing the relative risk posed by various debris sources.


Two key variables affect the ET-124 PRA, the PDL repair release rate and release mass estimates. SE&I approached the release rate estimate by assuming 1 repair out of 500 would be lost, given the performance history of similar repairs on previous missions [ref. 21]. The history of PDL repair losses from the LO2 ogive (the area of primary interest and that which poses the highest flight risk due to the potential for debris transport to critical locations on the orbiter) has been difficult to ascertain due to limitations inherent in flight imagery. Clearly, no wholesale loss of PDL repairs has been observed but estimates of actual repair losses over the history of the Shuttle Program are not definitive with verbal estimates ranging from none to two. SE&I assessed the sensitivity of the 1/500 estimate by doing a comparative analysis using a 1/100 release rate. Resultant failure probabilities ranged from 1:4000 for the lower rate to 1:800 for the higher [ref. 21]. NESC concurs with the approach, given the absence of anything more substantive on which to base the analysis; however, the resultant uncertainty is high and cannot be taken as a discrete estimate of flight risk.

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SE&I approached the release mass estimate by assuming complete repairs would be lost from the tank and that the total mass of any given repair would thus provide a conservative estimate of the debris mass. Only those repairs with a mass greater than the 0.004 lbm deterministic limit and located in the critical debris zone ($\phi = \pm 110$ degree +Z region of the tank) were used for initial analyses. While this approach simplifies the analysis, it does not address the physics underlying V-dP foam losses and may not be conservative. A divot would originate at a void in the PDL repair. As it is released it typically tears away overlying material, resulting in a cone-shaped chunk. A divot shaped like the frustum of a cone would be expected to have a cone half angle of 60 degrees, with the smaller end having the surface area of the original defect. The resultant mass of PDL and the NCFI in the divot can easily exceed that of the repair. When the mass of the PDL repair itself is used as the mass loss, there are only 86 repairs with masses >0.004 lbm. When the adjacent NCFI torn out in the divot is included, there are more than 700 possible losses with masses above 0.004 lbm. Adding the adjacent NCFI volume significantly increases the number of repairs which must be assessed but provides a more realistic estimate of the risk. NESC recommended the PRA be conducted using divot masses so-calculated rather than performing the initial sorting by the total repair mass initially planned. The NESC analysis methodology and results are at Appendix I. The Program concurred with this recommendation.

7.5 Summary


Tests and analyses performed to substantiate the repairs planned for ET-124 were well-formulated and provide an adequate foundation for flight rationale. The biggest weakness in flight rationale is the assumption that the sub-surface void distribution for on-tank PDL repairs is in family to that observed in repairs done at MAF. Although no direct evidence exists to substantiate this assumption, the NESC concurs with flight on the strength of the process controls known to be in place when the PDL repairs were implemented.

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8.0 Findings, Observations, and Recommendations

8.1 Findings


- F-1.** Inspections and engineering assessment conducted by ET Project were rigorous and well-implemented; however the potential that some residual crushed foam remains on ET-124 cannot be eliminated.
- F-2.** Review of test databases indicates crushed foam tests do not fully envelope ET-124 due to differences in magnitude, rate, and cross-sectional area over which test samples were crushed.
- F-3.** Debris release in excess of deterministic limits due to residual crushed foam on ET-124 is unlikely as is the potential for accelerated erosion.
- F-4.** The additional component of risk offered by multiple repairs is difficult to quantify, but this risk is mitigated by established process controls.
- F-5.** Modified sand and blend surface waviness and wall angle criteria are test-substantiated and adequate to address flight safety risks.
- F-6.** Eleven sites selected for S&B repair should be redesignated for PDL on the basis of icing potential as demonstrated by the NESC non-dimensionalized analysis.
- F-7.** Specified repair density limits (repairs per square foot and distance between repairs) are test-validated with no adverse effect on NCFI integrity.
- F-8.** Additional controls on PDL repairs are necessary to ensure pour time and red dye application requirements are not violated.
- F-9.** KSC training procedures do not include steps for dissection and analysis of PDL repairs, and the test panels used for KSC training are not made with NCFI foam.
- F-10.** Lighting in the LOX ogive work area was insufficient for some tasks.
- F-11.** The existing body of PDL repair void data is summarized in Appendix B, Table B-1 and assumed applicable to the repairs done on ET-124, but no recorded data exists to validate this assumption.
- F-12.** PDL repair processes do not provide for collection of in-process data.

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- F-13.** Controls applied to the PDL repair process are adequate, but some process catches and escapes have been noted. The large number of repairs applied to the tank increases the possibility that undetected process escapes may have occurred.
- Conathane® application issue drove removal of 32 repairs
 - Collateral damage occurred during mold removal
 - Some under-fills and surface voids were noted which required re-repair
 - Omission of post-repair Shore-A hardness testing for 88 repairs
- F-14.** PDL repair processes could be improved through a detailed P-FMEA and process sensitivity study.
- F-15.** Debris release above deterministic limits or accelerated TPS recession in the areas of the BX-265 spray repairs is unlikely.
- F-16.** Total repair mass does not provide a conservative estimate of potential debris mass loss. Debris mass may exceed total repair mass when cone-shaped divot models are employed for mass calculations.

8.2 Observations

- O-1.** Review of repair processes and flight history highlight no areas of concern not already addressed.
- O-2.** Primary issue facing ET-124 is the cumulative risk posed by repeated performance of process-sensitive repair tasks.
- O-3.** Sand-and-Blend, PDL and BX-265 repairs are process-sensitive tasks and developmental testing and process controls are the primary debris risk mitigators.
- O-4.** The PDL repair process is known to generate non-detectable sub-surface voids which can liberate debris in flight.
- O-5.** STS-96 flight history (ET-100 hail damage), and STS-70 flight history (woodpecker damage) show minimal foam loss. Orbiter damage seen on the STS-96 mission coincides with changes made to ET intertank TPS and was probably caused by loss of “popcorn” form from that area of the tank.
- O-6.** Few repair losses have been noted from other flight tanks, especially from the LO2 tank region, despite the large number of repairs performed; however, flight experience is


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based on limited field-of-view, post-sep imagery and is subject to some limitations.

- O-7.** Previous repairs have been done using processes that are similar, but not identical, to those employed for ET-124. Chief differences include the vertical attitude of the tank and modifications implemented to facility “mass production” of ET-124 repairs.
- O-8.** PRA is useful only as a tool for comparing relative risks from debris sources and should not be taken as a measure of the absolute risk.
- O-9.** Increment of risk assumed in multiple PDL repairs is difficult to quantify.
- O-10.** Repair release rates drive the risk assessment results but those rates used in the STS-117 PRA are estimates and subject to uncertainties inherent in limited data.

8.3 Recommendations

- R-1.** Proceed with flight of ET-124 as-repaired [F.1 – F.15].
- R-2.** Perform additional crushed foam testing on panels with simulated hail damage *(implemented)* [F.2].
- R-3.** Perform PDL repairs instead of sand-and-blends at 11 locations identified as high-risk for icing *(implemented)* [F.6].
- R-4.** Collect in-process data during performance of in-place PDL repairs *(not implemented)* [F.11, F.12].
- R-5.** Implement specific improvements to address concerns noted during human factors team review of the KSC PDL repair process *(implemented)* [F.8, F.10]
 - Time PDL pours
 - Document red dye application processes in specific work steps vs. procedural notes
 - Improve workplace lighting before application of PDL repairs
- R-6.** Update the KSC PDL repair certification/recertification procedures to include steps for dissection of the PDL pours made on foam test panels. After dissection, require technicians to identify and measure any subsurface voids that are present [F.9].
- R-7.** Perform formal Process Failure Modes and Effects Analyses (P-FMEAs) on ET repair processes in order to identify and mitigate potential process escapes and process catches [F.13, F.14].

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- R-8.** Mass estimates based on V-dP physics (cone-shaped divot with 60-degree wall angles) should be used for PRA mass loss estimates.

9.0 Lessons Learned

- L-1.** Performing trend analyses on process catches and process escapes will provide a more proactive and robust approach for identifying and fixing process control issues. The Space Shuttle Program (SSP) currently requires trending and reporting only process escapes to the SSP Quality Panel and SSP managers [ref. 18] [F.13, F.14]. The SSP definitions of process escapes and process catches are inconsistent with the industrial and human factors engineering terminology used in industry.

10.0 Definition of Terms

Corrective Actions	Changes to design processes, work instructions, workmanship practices, training, inspections, tests, procedures, specifications, drawings, tools, equipment, facilities, resources, or material that result in preventing, minimizing, or limiting the potential for recurrence of a problem.
Finding	A conclusion based on facts established during the assessment/inspection by the investigating authority.
Lessons Learned	Knowledge or understanding gained by experience. The experience may be positive, as in a successful test or mission, or negative, as in a mishap or failure. A lesson must be significant in that it has real or assumed impact on operations; valid in that it is factually and technically correct; and applicable in that it identifies a specific design, process, or decision that reduces or limits the potential for failures and mishaps, or reinforces a positive result.
Observation	A factor, event, or circumstance identified during the assessment/inspection that did not contribute to the problem, but if left uncorrected has the potential to cause a mishap, injury, or increase the severity should a mishap occur.
Problem	The subject of the independent technical assessment/inspection.
Recommendation	An action identified by the assessment/inspection Team to correct a root cause or deficiency identified during the investigation. The


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recommendations may be used by the responsible C/P/P/O in the preparation of a corrective action plan.


Root Cause Along a chain of events leading to a mishap or close call, the first causal action or failure to act that could have been controlled systemically either by policy/practice/procedure or individual adherence to policy/practice/procedure.

11.0 List of Acronyms

AA	Associate Administrator
CERB	Chief Engineer's Review Board
ET	External Tank
GUCP	Ground Umbilical Carrier Plate
ICD	Interface Control Document
IFA	In-Flight Anomaly
IFRs	Ice Frost Ramps
IRT	Independent Review Team
JSC	Johnson Space Center
KSC	Kennedy Space Center
LCC	Launch Commit Criteria
LH2	Liquid Hydrogen
LM	Lockheed-Martin
LO2	Liquid Oxygen
MSFC	Marshall Space Flight Center
MAF	Michoud Assembly Facility
MMC	Martin Marietta Corporation
MMT	Mission Management Team
MR	Material Review
MRB	Material Review Board
NESC	NASA Engineering & Safety Center
NCFI	North Carolina Foam Institute
NSTS	National Space Transportation System
OCE	Office of Chief Engineer
OML	Outer Mold Line
OMRS	Operation and Maintenance Requirements and Specifications
PAL	Protuberance Air Load
PDL	Polymer Development Laboratory
PRA	Probabilistic Risk Assessment
QC	Quality Control


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S&MA	Safety and Mission Assurance
SE&I	Systems Engineering and Integration
SLA	Super-Lightweight Ablator
SLWT	Super Lightweight Tank
SOMD	Space Operations Mission Directorate
SRB	Solid Rocket Booster
SSME	Space Shuttle Main Engine
SURFICE	Surface Ice Tool
SSP	Space Shuttle Program
TIM	Technical Interchange Meeting
TPS	Thermal Protection System
USA	United Space Alliance
USI	Use As Inspected
USR	Use As Repaired
V&V	Verification and Validation
VAB	Vehicle Assembly Building


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Volume II: Appendices

- A: NESC Request Form
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- C: List of Documents, Tests and Analyses Reviewed by the NESC
- D: (Resereved)
- E: Process Demonstration for Multiple PDL Pours per Single Syringe Load
- F: NESC Physically Based Non-Dimensionalization of Icing Probability
- G: NESC Probability of Launch Based on Icing
- H: NESC Cryogenic Moisture Uptake Core Study
- I: NESC Expected PDL 1034 Mass Loss Assessment
- J: Evaluation of the Inspection of Nose Cone, GH2 Pressurization Line Fairing, and Intertank Access Door for ET 124


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Appendix A. NESC Request Form

NASA Engineering and Safety Center Request Form		
Submit this ITA/I Request, with associated artifacts attached, to: nrbexecsec@nasa.gov , or to NRB Executive Secretary, M/S 105, NASA Langley Research Center, Hampton, VA 23681		
Section 1: NESC Review Board (NRB) Executive Secretary Record of Receipt		
Received (mm/dd/yyyy h:mm am/pm) 3/5/2007 12:00 AM	Status: New	Reference #: 07-005-E
Initiator Name: William Gerstenmaier	E-mail: william.h.gerstenmaier@nasa.gov	Center: HQ
Phone: (202)-358-2015, Ext	Mail Stop:	
Short Title: STS-117 Hail Repair Assessment		
Description: This is a quick turn-around assessment		
Source (e.g. email, phone call, posted on web): e-mail		
Type of Request: Assessment		
Proposed Need Date:		
Date forwarded to Systems Engineering Office (SEO): (mm/dd/yyyy h:mm am/pm):		
Section 2: Systems Engineering Office Screening		
Section 2.1 Potential ITA/I Identification		
Received by SEO: (mm/dd/yyyy h:mm am/pm): 3/5/2007 12:00 AM		
Potential ITA/I candidate? <input checked="" type="checkbox"/> Yes <input type="checkbox"/> No		
Assigned Initial Evaluator (IE): This has been approved out-of-board by Tim Wilson on 3/5/2007. Tim Wilson will be leading this. There is no Initial Evaluation required.		
Date assigned (mm/dd/yyyy): 3/5/2007		
Due date for ITA/I Screening (mm/dd/yyyy):		
Section 2.2 Non-ITA/I Action		
Requires additional NESC action (non-ITA/I)? <input checked="" type="checkbox"/> Yes <input type="checkbox"/> No		
If yes:		
Description of action:		
Actionee:		
Is follow-up required? <input checked="" type="checkbox"/> Yes <input type="checkbox"/> No If yes: Due Date:		
Follow-up status/date:		
If no:		
NESC Director Concurrence (signature):		
Request closure date:		
Section 3: Initial Evaluation		
Received by IE: (mm/dd/yyyy h:mm am/pm):		
Screening complete date:		
Valid ITA/I candidate? <input type="checkbox"/> Yes <input type="checkbox"/> No		
Initial Evaluation Report #: NESC-PN-		
Target NRB Review Date:		

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Section 4: NRB Review and Disposition of NCE Response Report			
ITA/I Approved: <input type="checkbox"/> Yes <input type="checkbox"/> No		Date Approved:	
ITA/I Lead: , Phone () - , x		Priority: - Select -	
Section 5: ITA/I Lead Planning, Conduct, and Reporting			
Plan Development Start Date:			
ITA/I Plan # NESC-PL-			
Plan Approval Date:			
ITA/I Start Date		Planned:	Actual:
ITA/I Completed Date:			
ITA/I Final Report #: NESC-PN-			
ITA/I Briefing Package #: NESC-PN-			
Follow-up Required? <input type="checkbox"/> Yes <input type="checkbox"/> No			
Section 6: Follow-up			
Date Findings Briefed to Customer:			
Follow-up Accepted: <input type="checkbox"/> Yes <input type="checkbox"/> No			
Follow-up Completed Date:			
Follow-up Report #: NESC-RP-			
Section 7: Disposition and Notification			
Notification type: - Select -		Details:	
Date of Notification:			
Final Disposition: - Select -			
Rationale for Disposition:			
Close Out Review Date:			

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Form Approval and Document Revision History

Approved: _____ NESC Director	_____ Date
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Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Release	Principal Engineers Office	29 Jan 04

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Appendix B. Performance History of PDL Repairs and Crushed Foam

Table B-1 Performance History of PDL Repairs

Source	Description	Conditions	Results	Assessment	At Divoting Depth Limit of Largest Void
809-9621 PDL 1034 Application/Processing Assessment V&V	Post-Columbia assessment of pre-Columbia V&V	101 horizontal pours and 49 vertical pours	Internal void formation was deemed to be low probability in horizontal applications, but higher in vertical and overhead pour positions. The actual void size was not recorded but was below the 0.5 x 0.5" pre-Columbia threshold.	Points to 0.5" cylindrical voids.	Critical depth for 0.5" cylinder is 0.8" deep and results in 0.005 lbm divot assuming that the entire divot is PDL.
809-9972 Delta Validation of Longeron Plug Pull Restoration V&V	New Validation Data with Dissections	50° from horizontal and 5 accepted pours.	3 of the 5 accepted pours had voids	Range of slot sizes. Maximum found 0.4".	Critical depth for 0.4" slot is 0.8" and results in a 0.004 lbm divot from 0.1" slot, 0.005 lbm divot from 0.2" slot, and 0.007 lbm divot from 0.3" slot assuming entire divot is PDL.
809-9972 TPS Process Assessment Summary, Maximum Expected Defect Determination for Fly-As-Is ET TPS Hardware Dissection	Partial dissection of TPS on 4 external tanks	19 repairs dissected	15 process cylindrical defects and 25 process slot defects. Largest process cylinder was 0.7". Largest process slot was 0.4".	Largest process cylinder was 0.7". Largest process slot was 0.4"	Critical depth for 0.7" cylinder is 0.9" deep and results in 0.008 lbm divot assuming entire mass is PDL.

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Source	Description	Conditions	Results	Assessment	At Divoting Depth Limit of Largest Void
809-9440 TPS Process Assessment, Maximum Expected Defect	Dissection data of PDL repairs of plug-pulls			Geometric Cylinders = 1.5" Processed Cylinders = .98" Geometric Slots = .84" Processed Slots = .56"	
826-2048-85, "Effects of PDL-1034 Repairs on Downstream Recession of NCFI 24-124", 1997	NCFI with standard PDL Repairs	Hot gas test	Repaired and downstream areas showed acceptable performance	Verification of standard PDL repair	
No Test Report Number, "Woodpecker Divot Testing in the Improved Hot Gas Facility	NCFI with Standard PDL repairs and sand and blends. 5 sand and blends tested	Hot gas test	Normal recession - no debris generation	Verification of standard PDL repair. Verification of sand and blend if damaged area is at bottom of sand and blend.	
NASA TM 110857, "Debris/Ice/TPS Assessment and Integrated Photographic Analysis of Shuttle Mission STS-70," 1995	Test panels with multiple PDL repairs of varying sizes	Hot gas test	No significant debris loss or evidence of unacceptable recession was observed	Verification of PDL repairs in areas having multiple damage sites	
809-8807, "ET-124 Crushed Foam Testing", Addendum 6, no date	Requalification of PDL material for ET-124 due to new supplier. Test panels with multiple PDL and sand and blend repair areas.	Hot gas test	PDL requalified. Demonstrated acceptable performance of multiple PDL and sand and blend repairs in the LO2 ascent environment.	Verification of PDL and sand and blend repairs in areas having multiple damage sites	



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Table B-2 Performance History of Crushed Foam

Source	Description	Conditions	Results	Assessment
ETTR-621, "Hail Damage Simulation on NCFI24-124"	27 2.4" net NCFI panels Steel balls used to simulate hail Various angles of incidence Also machined panels	ambient	1" steel balls created 0.6" deep crushed foam at bottom of cavity. Smaller than maximum STS-117 hail size.	Shows that crushed foam exists below visual zone
809-9910, Thermal Vacuum Testing of Crushed Foam with Cryogenic Backface," Apr, 2006	Crushed foam via walking loads through the walking mats	vacuum/ IR	No debris loss from damaged areas. 300# load applied over large area (~4"Φ).	Limited – invisible damage zones on ET-124 are caused by a very different process
809-9954, "Thermal Evaluation of Crushed ET TPS in the Improved Hot Gas Facility," Apr 2006.	6 net spray and machined iNCFI panels, each with 6 crush regions – 3 1x1/2" ellipses and 3 4" circles, crush depth 5, 15, and 20% Also BX, PDL	Hot gas	Single foam loss from 20% crush area on machined panel. Crush mechanism may not be same as for hail	Single foam loss event from crushed foam

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Source	Description	Conditions	Results	Assessment
809-9890, "Red Dye and Shearography Evaluation as Determination by Tensile Strength of Crushed Foam," May 2006.	Net spray NCFI panels subjected to crush loads from 4" diameter disk. Also Machined panels, BX, PDL	ambient	NCFI is sensitive to crushing	Limited – this was a detection test but it did show that NCFI is vulnerable to crushing
809-8603, "Thermal Vacuum Testing: Recession Characterization of Crushed TTPS," May 2006.	6 net spray NCFI panels, each with 6 crush regions – 3 1x1/2" ellipses and 3 4" circles with radiused edges, slow crush depth 5, 15, and 20%. Also Machined panels, BX, PDL	Vacuum/IR	Normal recession – no debris generation. Crush mechanism not be same as for hail - speed	Some relevance to undetected damage
809-9954, "IFA, AC-14, Quick Look, Evaluation of Working-Walking Loads	1.2" thick net spray NCFI panels subjected to slow crush loads from 3" diameter disk and 4" sphere	vacuum/IR	Foam losses from panels with disk loads of 150 and 200 lbs. Load applied slowly over large area	Two divoting events from crushed foam
809-9655, "Ice/frost Characterization testing"	5 net spray NCFI panels 1" and 2" deep crushes (25% and 15%, respectively)		Ice formed at crushed foam	Ice/frost can result from damaged foam

Source: Wilson, T., "NESC STS-117 Hail Damage Repair Assessment, Project Status," Mar 21, 2007.


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Appendix C. List of Documents, Tests and Analyses Reviewed by the NESC


Document Type	Document Description	Document	Impacted	Date Last Updated
Overview				
Presentation	Presentation summarizing the damage, repair approach and verification	Overview Briefing	Info Only	4/27/07
Applicable Documents				
Level II Requirement	Flight and Ground System Specification	NSTS 07700 Volume X – Book 1	Info Only	4/27/07
Level II Requirement	Ice/Debris Inspection Criteria	NSTS 08303	Info Only	4/27/07
Level II Requirement	Expected Debris Generation and Impact Tolerance Requirements, Groundrules, and Assumptions	NSTS 60559	Info Only	4/27/07
ICD	Moldline & Protuberances ICD	ICD-2-00001	Info Only	4/27/07
ICD	Space Shuttle/Launch Pad & Platform ICD possible	ICD-2-0A002	Info Only	4/27/07
Level II Requirement	OMRSD Requirements - Operation & Maintenance Requirements & Specification Document	NSTS 08171 – File IV - ET OMRDSs File II Vol 1 , Vol 3 , Vov 4	Info Only	4/28/07

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Level II Requirement	LCC - Launch Commit Criteria	NSTS 16007 – Section 17 – External Tank Subsystems	Info Only	4/28/07
Environments	Documentation of Mission Specific Heating for Launch Probability	SE&I Thermal Environments	Info Only (available on request)	5/2/07
End Item Specification (EIS)	ET Contract End Item Specification	CPTO1M09A, END ITEM (CEI) SPECIFICATION - PART I	Info Only	4/28/07
Verification Plan	ET requirement verification plan	TM01	Info Only	4/28/07
Affected Documents				
Level II Requirements	Applicable Environments Changes	Thermal Environments – no change	No	5/2/07
End Item Specification (EIS)	Revisions to Contract End Item Specification	N/A	No	5/2/07
Verification Plan	ET requirement verification plan	ET-124 Repair affected Verification Matrix LO2 Tank Acreage TPS • T521C-ET124 Intertank Acreage TPS • T522C-ET124	Impacted	5/1/07
FMEA/CIL	Changes to baseline / violations as the result of ET-124 repair	CIL Item Monitoring Discussion	Impacted	4/27/07
ICD	Changes to baseline / violations as the result of ET-124 repair	Waiver IRN if required	TBD	ECD ? Impact will be pending final assessment of

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				As-Built
OMRSD	Changes to baseline / violations as the result of ET-124 repair	N/A	No	4/27/07
LCC	Changes to baseline / violations as the result of ET-124 repair	N/A	No	4/27/07
Hazards	Changes to baseline / violations as the result of ET-124 repair	<ul style="list-style-type: none"> T.02 - Loss of ET Thermal Protection System (changes) T.04 - ET Ice Debris/Damage (changes) 	Impacted	5/02/07 Planning update – not available for RVR Available for FRR
MUAs	393D	Updated MUA for PDL 1034 (NCFI 26-007)	Info Only	4/27/07
MUAs	0421C	Updated MUA for BX-265	Info Only	4/27/07
Required Testing				
Test Plan / Report	Changes to TPS materials - PDL-1034 (NCFI 26-007)	Plan <ul style="list-style-type: none"> MS-06-040 MS-06-040 Rev 1 MS-06-040 Rev 1, Add 1 Report <ul style="list-style-type: none"> 809-8544-1 809-8544-2 	Impacted	4/28/07
Test Plan / Report	Changes to TPS materials – BX-265 (Polyol source change) Qualification test plan/report	Plan <ul style="list-style-type: none"> 809-8600 Rev A 809-8600 Rev A Add 1 809-8600 Rev A Add 2 Report <ul style="list-style-type: none"> 809-8601 R1 	Impacted	4/28/07

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Forward Ogive Repair Testing				
<i>Test Plan / Report</i>	Demonstration	Plan <ul style="list-style-type: none"> 809-8802 Report <ul style="list-style-type: none"> 809-8803 Flash Report 	Impacted	5/2/07
<i>Test Plan / Report</i>	Hot Gas Testing	Plan <ul style="list-style-type: none"> 809-8804 809-8804 Amendment 1 809-8804 Amendment 2 Report <ul style="list-style-type: none"> 809-8805 Flash Report 	Impacted	4/28/07
Repair Testing 809-8807 Combined Flash Report – All Addenda				
<i>Test Plan / Report</i>	Addendum 1, Sand and Blend Test	<ul style="list-style-type: none"> 809-8807, Add. 1 (Plan) 809-8808 - ET 124 HAIL DAMAGE CRUSHED FOAM TESTING – Addendum 1 Sand & Blend Thermal Testing (Report) 	Impacted	4/28/07 Report ECD ?
<i>Test Plan / Report</i>	Addendum 2, Hail Damage Simulation	<ul style="list-style-type: none"> 809-8807, Add. 2 (Plan) 809-8836 - ET 124 HAIL DAMAGE CRUSHED FOAM TESTING – Addendum 2 Hail Damage 	Impacted	4/28/07 Report ECD ?

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		Simulation (Report)		
Test Plan / Report	Addendum 3, Intertank Hot Gas Recession Test	<ul style="list-style-type: none"> • 809-8807, Add. 3 (Plan) • 809-8837 - ET 124 HAIL DAMAGE CRUSHED FOAM TESTING – Addendum 3 Intertank Hail Damage Hot Gas Test (Report) 	Impacted	4/28/07 Report ECD ?
Test Plan / Report	Addendum 4, Dynamic vs Static Foam Crushing Test	<ul style="list-style-type: none"> • 809-8807, Add. 4 (Plan) • 809-8838 - ET 124 HAIL DAMAGE CRUSHED FOAM TESTING – Addendum 4 Dynamic vs. Static Crushed Foam Hot Gas Test (Report) 	Impacted	4/28/07 Report ECD ?
Test Plan / Report	Addendum 5, Barely Visible Damage “BVD” Hot Gas Test	<ul style="list-style-type: none"> • 809-8807, Add. 5 (Plan) • 809-8839 - ET 124 HAIL DAMAGE CRUSHED FOAM TESTING – Addendum 5 Barely Visible Damage Hot Gas Test (Report) 	Impacted	4/28/07 Report ECD ?
Test Plan / Report	Addendum 6, PDL Repair Hot Gas Test	<ul style="list-style-type: none"> • 809-8807, Add. 6 (Plan) • 809-8807, Add. 6 A1 (Plan) • 809-9940 - ET 124 HAIL DAMAGE CRUSHED FOAM TESTING – Addendum 6 PDL Repair Hot 	Impacted	4/28/07 Report ECD 5/6

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		Gas Test (Report)		
Test Plan / Report	Addendum 7 & 8, Barely Visible Damage “BVD” Icing and PDL Thermal Vac Test	<ul style="list-style-type: none"> • 809-8807, Add. 7/8 (Plan) • 809-8841 - ET 124 HAIL DAMAGE CRUSHED FOAM TESTING – Addendum 7/8 Barely Visible Damage / PDL Repair Thermal Vac Test (Report) 	Impacted	4/28/07 Report ECD 5/11
Test Plan / Report	Addendum 9, Intertank Thermal Test	<ul style="list-style-type: none"> • 809-8807, Add. 9 (Plan) • 809-8842 - ET 124 HAIL DAMAGE CRUSHED FOAM TESTING – Addendum 9 MSFC Simulated Hail Damage Thermal Vac Test (Report) 	Impacted	4/28/07 Report ECD ?
Test Plan / Report	Addendum 10, Hot Gas Test	<ul style="list-style-type: none"> • 809-8807, Add. 10 (Plan) • 809-8843 - ET 124 HAIL DAMAGE CRUSHED FOAM TESTING – Addendum 10 LO2 Tank Hail Damage Hot Gas Test (Report) 	Impacted	4/28/07 Report ECD ?
Plug Pull Failure Testing - Cat 3				
Test Plan / Report	Test #2: Plug pull re-core	LWR #21958 Flash Report	Impacted	05/02/07 Report ECD 5/7
Test Plan / Report	Test #3: Insecticide	LWR #21953 Flash Report	Impacted	05/02/07 Report ECD 5/7

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Related Analyses				
<i>Analysis Results</i>	Thermal Analysis - Documentation of analysis results that support the as-built configuration	<p>Launch Probability</p> <ul style="list-style-type: none"> • 4140/T-07-3016 - Assessment of Launch Probability with ET-124 Hail Damage <p>Icing Test Results</p> <ul style="list-style-type: none"> • 4140/T-07-3017 - Sand/Blend Criteria for Icing for ET-124 Repair Assessments for the LO2 Tank <p>Heat Leaks</p> <ul style="list-style-type: none"> • 4140/T-07-3013 - Documentation of LO2 Heat Leak Assessment for ET-124 Hail Damage <p>LO2 acreage</p> <ul style="list-style-type: none"> • 4140/T-07-3014 - Request for Stress Assessment of LO2 Tank Temperatures for ET-124 Hail Damage <p>Pencil Sharpener Repair</p> <ul style="list-style-type: none"> • 4140/T-07-3008 - Thermal Analysis of Pencil Sharpener Repair at Station 372 on ET-124 <p>Pencil Sharpener Repair</p> <ul style="list-style-type: none"> • 4140/T-07-3018 - ET-124 	Impacted	05/03/07

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		<p>Hail Damage LO2 Ogive Structural Temperature at XT 387 with BX/NCFI Repair</p> <p>Pencil Sharpener Repair</p> <ul style="list-style-type: none"> • 4140/T-07-3021 - ET-124 Hail Damage LO2 Ogive Structural Gradients for Divot Analysis at XT 375 with BX/NCFI Repair <p>Pencil Sharpener Repair</p> <ul style="list-style-type: none"> • 4140/T-07-3019 - Aerothermal Testing of the BX-265 over NCFI 24-124 Forward Ogive Machined Area (Pencil Sharpener Area) Repair Due to Hail Damage on ET-124 <p>Intertank-structure</p> <ul style="list-style-type: none"> • 4140/T-07-3012 - Thermal Analysis of Intertank Zones for ET-124 Damage Assessment <p>LO2 entry analysis</p> <ul style="list-style-type: none"> • 4140/T-07-3020 - ET Reentry Analysis for ET-124 LO2 Tank Hail Damage <p>Methodology for Cavities</p> <ul style="list-style-type: none"> • 4140/T-07-3010 - Sand/Blend 		
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		Criteria for Heating for ET-124 Thermal Analysis Assessments		
<i>Analysis Results</i>	Stress Analysis - Documentation of analysis results that support the as-built configuration	4130-07-01 - ET 124 Hail Damage LO2 Tank Structural Assessment 4130-07-02 - ET 124 Hail Damage Intertank Structural Assessment 4130-07-03 - ET 124 Hail Damage Composite Assessments	Impacted	ECD
<i>Analysis Results</i>	Propulsion Analysis - Documentation of analysis results that support the as-built design	4160/P-07-4002 - Assessment of ET-124 Minimum Foam Thickness Requirements on LO2 Tank Ullage Pressure and EOR Propellant Load	Impacted	05/03/07
Other Information				
Historical Documents				
<i>Review Data</i>	ET-124 Hail Damage TIM	#1 ET-124 Hail Damage Technical Interchange Meeting 3/14/07	Info Only	5/02/07
<i>Presentations – TSC / CERB</i>	ET-124 Hail Damage TSC / CERB briefings	TSC Briefings 4/5/07 ET-124 Component Dispositions 4/5/07 Spray Demonstration results CERB Briefings 3/6/07 ET Hail Damage assessment 3/12/07 ET-124 Repair Assessment Approach 3/12/07 Red Dye and crushed foam	Info Only	4/28/07

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		3/27/07 ET-124 PDL Repair Reduction 3/27/07 ET-124 Hail Damage Sampling Results 3/27/07 Planned Testing to Support Disposition of ET-124 Hail Damage 3/27/07 ET-124 LO2 Tank Temperature Assessment 3/27/07 LO2 Tank TPS Thickness requirements delta 3/27/07 ET-124 TPS Repair Impacts to STS-117 LO2 Tank EOR Propellant Load – PSIG 3/27/07 Thermal Sand and Blend criteria for icing 3/27/07 ET-124 LO2 Tank Thickness Map Mission specific 3/27/07 ET-124 New BX Spray 3/27/07 ET-124 Intertank Assessment Plan 4/12/07 809-8804 Hot Gas Brief Report 4/12/07 ET-124 Sand and Blend Criteria for Icing 4/18/07 ET Pencil Sharpener		
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		Repair demo testing update 4/18/07 Hail Damage Testing update 4/18/07 ET Project proposed ice ball testing		
<i>Presentations – TSC / CERB</i>	NCFI-007 (PDL-1034 replacement) TSC / CERB briefings	01/11/07 TSC: Review NCFI -007 (PDL-1034) material qualification test data 03/06/07 TSC: Review NCFI-007 (PDL-007) material qualification test data 04/05/07 TSC: Review NCFI-007 (PDL-1034) cryoflex monostrain test data	Info Only	4/30/07
<i>Presentations – TSC / CERB</i>	BX-265 re-qualification TSC / CERB briefings	11/30/06 TSC: Review chemical and mechanical property data of BX-265 material with Polyol source change 01/08/07 TSC: Review BX-265 material with Polyol source change hot gas test data 02/16/07 TSC: Review BX-265 Lot 1 Thermal Vac Thermal Conductivity data and Lot 2 Mechanical and Hot Gas 03/20/07 TSC: Review BX Lot 2 Thermal Vac and Thermal	Info Only	4/30/07

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		Conductivity data		
MPP	AFT OGIVE HAIL DAMAGE BX-265 REPAIR @ KSC (ET-124) (Montana demonstration)	ARK07014M10 Rev 2	Info Only	4/28/07
MPP	FWD OGIVE HAIL DAMAGE BX-265 REPAIR @ KSC (ET-124)	ARK07014K1 Rev 2	Info Only	4/28/07
Reference Info	ET-124 Hail Damage Repair Data	ET-124 Repair Data by Type	Info Only	5/02/07
Repair Summary	ET-124 Hail damage PDL repair calculations	Defect Data Summary	Info Only	4/30/07
Reference Info	Environment Update Process	PRCBD CR S071024LW Induced Environments Transmittal Process	Info Only	4/30/07
Reference Info	ET Project - Design Values for Non-Metallic Materials	809-9600	Info Only	4/30/07
Reference Info	Foam Losses	LO2 Acreage Foam Loss Summary	Info Only	5/01/07
Reference Info	Composite Intertank Door Ultrasonic Inspection Results	Report 2007-CB-01	Info Only	5/02/07
Reference Info	Composite GH2 Pressline Fairing Ultrasonic Inspection Results	Report 2007-CB-02	Info Only	5/02/07
Reference Info	Thermography of the Composite Nose Cone on ET-124	Report 2007-CB-03	Info Only	5/02/07
Presentation – NASA Senior Management	ET-124 Hail Damage Assessment and Verification Approach	ET-124 Hail Damage Assessment and Verification Approach Presentation	Info Only	5/03/07

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Review				
Actions for Reference				
ET PRCBD Actions	PRCBD S063595B (1-1) - ET Foam Minimum Thickness Requirements (STS-117) – Perform a LOX Tank heat leak assessment based on the final repair configuration of ET-124. Report to the SICB.	PRCBD S063595B and Response (Planned Presentation to SICB on 5/8)	Info Only	4/30/07 Response ECD 5/8
SEPARs	Transmittal of request to perform repair (from LM / KSC to USA / KSC)	All SEPARs with attachments	Info Only (available on request)	4/30/07
Action Requests	Transmittal of defect disposition and rationale for acceptance of disposition (from LM / MAF to LM / KSC)	All ARs	Info Only (available on request)	4/30/07

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Appendix D. (Reserved)

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Appendix E. Process Demonstration for Multiple PDL Pours per Single Syringe Load

On March 26 and March 27, 2007, USA performed two “process demonstrations” consisting of PDL pours on BX-265 foam test panels mounted vertically in a different area of the VAB than the actual ET work area. The primary goal of the demonstration was to develop and validate a revised method of PDL repairs using multiple PDL pours from a single syringe loaded with PDL foam. The intent of the new method was to increase overall efficiency of the repair process without sacrificing quality. The efficiency increase was desirable in order to get the repairs to a “production mode” that would support the milestones in the repair schedule. The results of the process demonstration were summarized in a United Space Alliance (USA) white paper provided to NESC on April 16, 2007.


TPSB SS20-613 and TPSB SS20-614 were the procedures developed to support the PDL pours in two test panels with 17 holes each. The process demonstration verified the methods for the production mode of PDL repairs at KSC.

The stated purpose of TPSB SS20-613 was to “verify PDL cream time in the VAB environment and determine syringe size and multiple holes proficiency.” (reference: USA white paper, April 16, 2007). The results of the TPSB SS20-613 procedure included the following:

- Determined a 1.7 cc of PDL foam in the syringe per cubic inch of estimated repair volume
- Determined that 3 holes in close proximity was the limit for one syringe
- Selected the 10 cc syringe size to support a three-hole injection
- Verified the PDL cream time supported the syringe method and a three-hole injection series

During TPSB SS20-613, mold failures were experienced from foam lifting the mold off the ET surface, which raised concerns regarding sub-surface voids. As a result, only hard molds were allowed in the repair methods. A double ring of sealant tape (“dum dum” putty) was also used to secure the hard mold to the ET. The sealant tape was a contributor to rework activities (i.e. sand and blend) when removal of the tape also lifted some of the surface ET foam (the “rind”) during mold removals.


The stated purpose of TPSB SS20 614 was to “demonstrate the multiple holes pour and to verify injection parameters and that lessons learned (from TPSB SS20 613) were incorporated” (reference: USA white paper, April 16, 2007)) into the final PDL repair procedure. Specific objectives of this demonstration included verifying that the subsurface void criteria were not

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violated and verifying technician proficiency (in addition to the proficiency already demonstrated during the proficiency already demonstrated during the certification/recertification process). The results of the TPSB SS20-614 procedure included the following:

- 17 of 17 test PDL repairs were free of subsurface voids. One of 17 repairs was an under fill.
- Verified by dissection that no subsurface void criteria (0.5 inch maximum) was violated on all test samples.

“Buy copies” of TPSB SS20-613 and TPSB SS20-614 were provided to NESC. No dissection measurements or photographs were collected as part of TPSB SS20-613 or TPSB SS20-614.

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Appendix F. NESC Physically Based Non-Dimensionalization of Icing Probability

Rationale

The External Tank Project devised a method of sorting the hail damage locations into deeper-than-normal sand and blend (S&B) and PDL repairs with a goal of minimizing the number of PDL repairs on the tank. This sorting was performed by identifying the icing potential of each prospective S&B repair. Those that had an icing probability of greater than 15 percent for a May through October launch were selected by the project to be repaired using PDL. To enable this sorting, the project set up an icing test in a natural convection chamber. A box fan was included in the test to allow for some forced convection. Liquid nitrogen-backed foamed panels with cavities of different depths and shapes were tested to identify the icing limits.

The results of the testing are shown in Figure J-1 along with the 327 damage locations included in the sorting. The line labeled as “test derived with wind” was developed directly from the tipping points identified in the icing tests. It was used to sort the repair sites into PDL and S&B, resulting in 26 suggested PDL repairs and 301 S&B repairs. Also, 3 repairs that fell into the S&B region were re-designated as PDL by the ET Project owing to a feeling of increased icing risk at these locations and depths.

A NESC preliminary investigation of the historic at KSC weather indicated that the 15 percent icing probability (85 percent launch probability) cutoff most likely coincided with wind speeds that would cause the heat transfer on the LO₂ ogive to be dominated by forced convection. This raised an issue with directly using the results of a natural convection test with limited forced convection to assess icing in the forced convection dominated launch conditions. In addition, it was noted that the sorting criteria did not take into account the fact that the new minimum foam thickness is 0.8 inch in the no-ice zone vs. 0.6 inch in the ice limitation zone. Therefore, the icing potential of the prospective S&B repairs on all zones of the tank cannot be represented using defect depth and foam thickness as the sole variables. Because of these factors, the NESC performed a physics-based non-dimensionalization of the icing potential to allow the relative icing potential of all prospective S&B repairs to be assessed.

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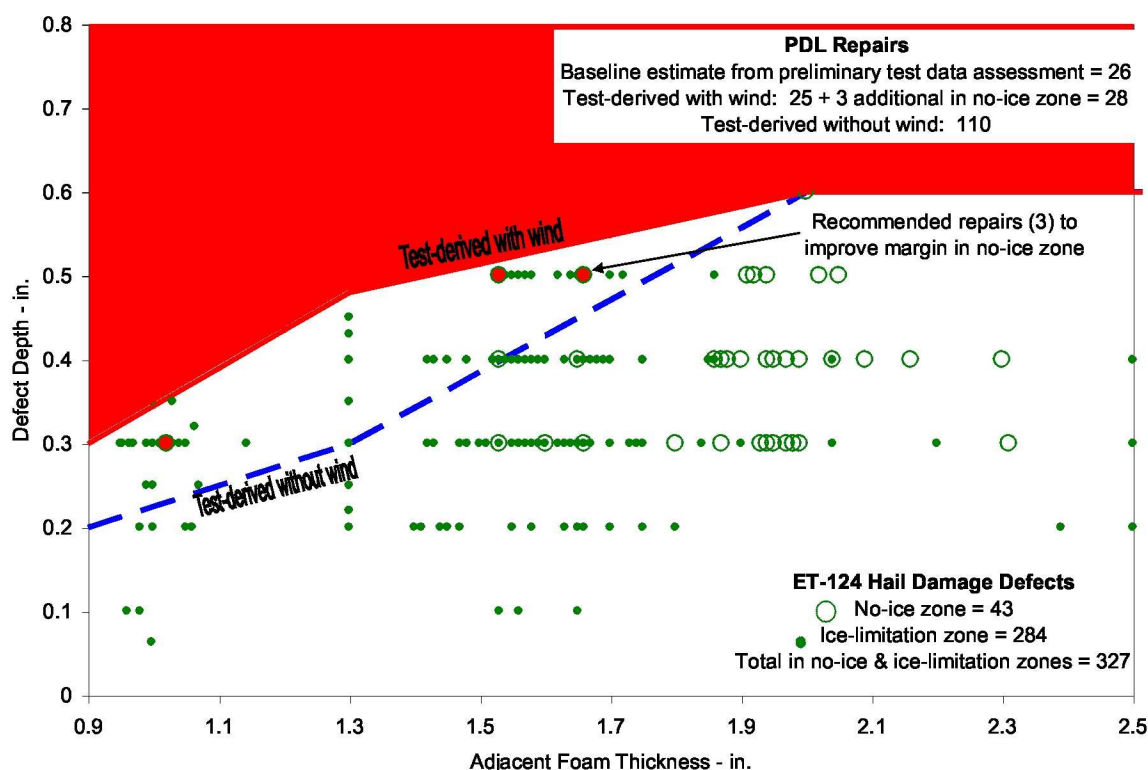



Figure F1 - Sand/Blend Criteria for Ice Zones (from Sand and Blend Criteria for ET-124 Icing Zones, Michelle Guillot. April 12, 2007)

Physics-Based Non-Dimensionalization

For foam on the oxygen tank at the minimum thickness, t_{\min} , for a given ambient temperature, T_{∞} , there is a value of the nominal convective coefficient, h_{nominal} , below which unacceptable icing can occur. This defines a critical surface temperature, $T_{\text{surface,critical}}$. The physical case is shown in Figure J-1.

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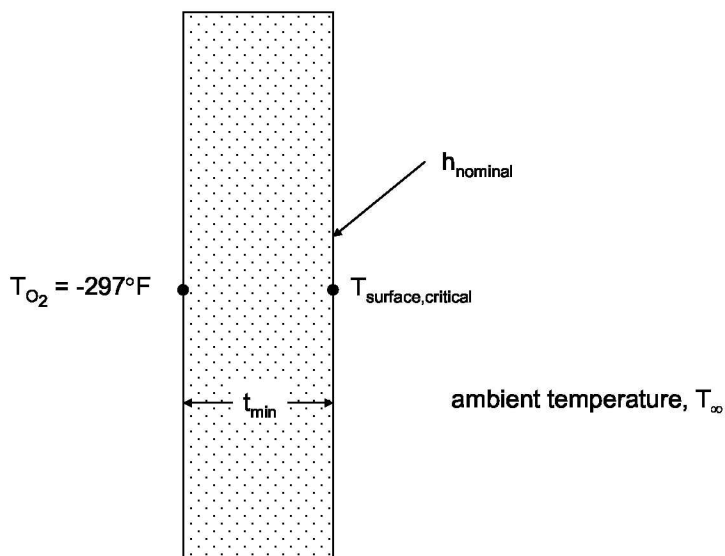


Figure F-2 – Physical Layout of Foam Heat Transfer

The heat transfer through the foam can be characterized by the thermal resistances shown in Figure J-2. Here, k_{eff} is the effective thermal conductivity of the foam and A is a characteristic surface area perpendicular to the heat transfer path.

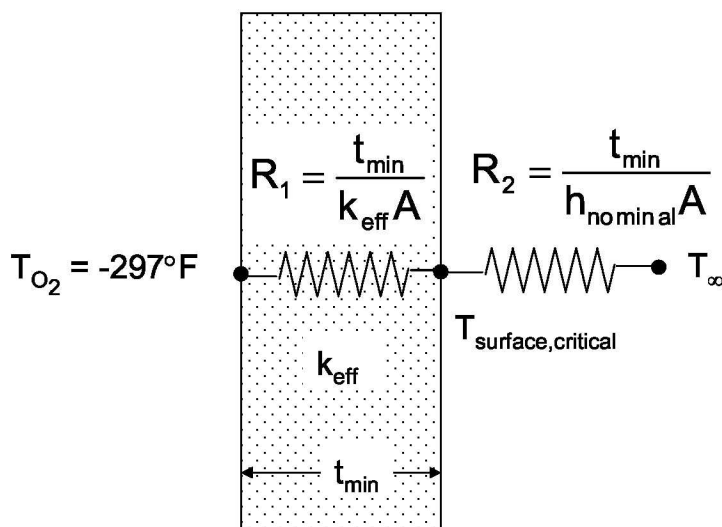


Figure F-3 –Thermal Resistances at the Minimum Foam Thickness

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To maintain the same icing probability as a large flat area at the minimum thickness, the surface temperature at the bottom of a sand and blend must be greater than or equal to critical surface temperature. A one-dimensional analysis allows the thermal resistances to the bottom of the cavity to be represented as shown in Figure J-3, where t is the foam thickness and h is the convection coefficient in the bottom of the cavity.

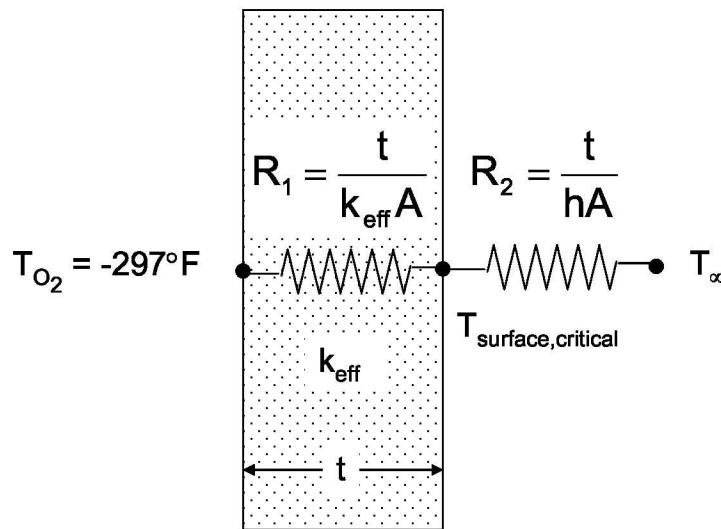


Figure F-4 – One-Dimensional Thermal Resistances at the Bottom of a Cavity


To maintain the same critical surface temperature for different foam thicknesses, the ratio of the two thermal resistances, R_1/R_2 must be the same in the two cases. This yields the following relationship for the convective coefficient at the bottom of the cavity required for equivalent surface temperature

$$h = h_{\text{nominal}} \frac{t_{\text{min}}}{t} \quad (1)$$

This result is independent of ambient temperature, the critical surface temperature, and the nominal heat transfer coefficient. If the convective coefficient at the bottom of the cavity is higher than the value calculated by eqn. (1), the icing potential is less than for a flat surface at the minimum foam thickness. Conversely, if the coefficient is lower than this value, there is a higher icing potential than for a flat surface at the minimum foam thickness.

At wind speeds exceeding 2 knots, the Reynolds number at the ogive exceeds 5×10^5 and the heat transfer mechanism on the tank surface is turbulent forced convection. In this case we might expect that the convective coefficient at the bottom of a cavity would be characterized by

- the local convection coefficient over a nearby flat surface

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- the cavity depth
- the cavity width
- the cavity shape.

Buckingham's Pi theorem suggests that we could express the relation in dimensionless form as

$$\frac{h}{h_{\text{nominal}}} = \text{fn} \left[\frac{\lambda}{d}, \text{shape} \right] \quad (2)$$

where λ is the cavity width and d is the cavity depth. For similar cavity shapes, the expression becomes

$$\frac{h}{h_{\text{nominal}}} = \text{fn} \left[\frac{\lambda}{d} \right] \quad (3)$$


Buckingham's Pi theorem says that h/h_{nominal} can be expressed as a single valued function of λ/d , but does not tell us anything about the shape of the curve. However, the physics of the airflow in the cavity suggest that for large values of λ/d , the cavity approximates a flat surface and h/h_{nominal} approaches unity. As λ/d decreases, the cavity becomes relatively steeper, reducing the airflow in the cavity, and reducing h/h_{nominal} .

The ET Project Test Results

The ET Project test-based recommendations are plotted using the appropriate dimensionless groups in Figure 5. The y-axis is the repair-specific convective coefficient ratio calculated from eqn. 1 that must be maintained to yield the same surface temperature as for a flat surface at the same thickness. Several conclusions are apparent from the figure. First, the ET recommended PDL repairs³ are clustered where the sand and blend repair would be deep and steep (low λ/d) and would need to maintain a high fraction of the flat surface heat transfer. Second, the three additional recommended PDL repairs⁴ are in a region where many other locations are also recommended for PDL repair. Third, there is some overlap between the recommendations for S&B and PDL repair.

³ Labeled "ET PDL" in the Figure 5.

⁴ Labeled "ET Extended PDL" in Figure 5

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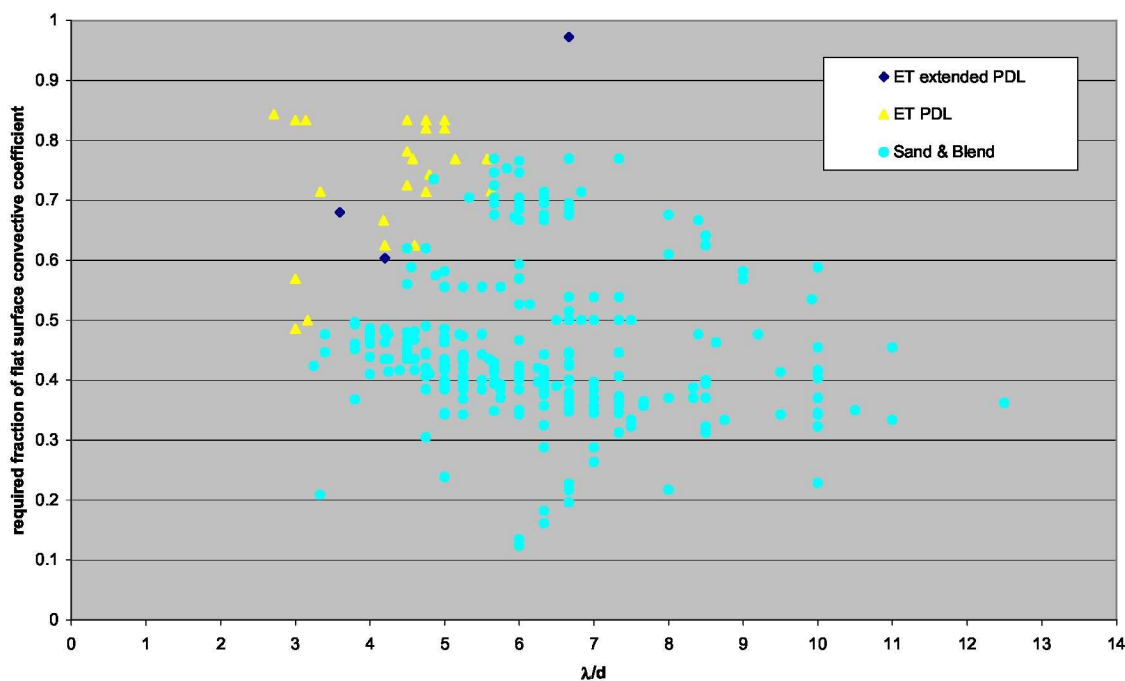



Figure F-5 – ET Project Test-Based Repair Recommendation

To address the repair method overlap, a cutoff line was drawn encompassing all the ET Project-recommended PDL repairs as shown in Figure J-6. The line has the expected upward slope as discussed in the previous section.

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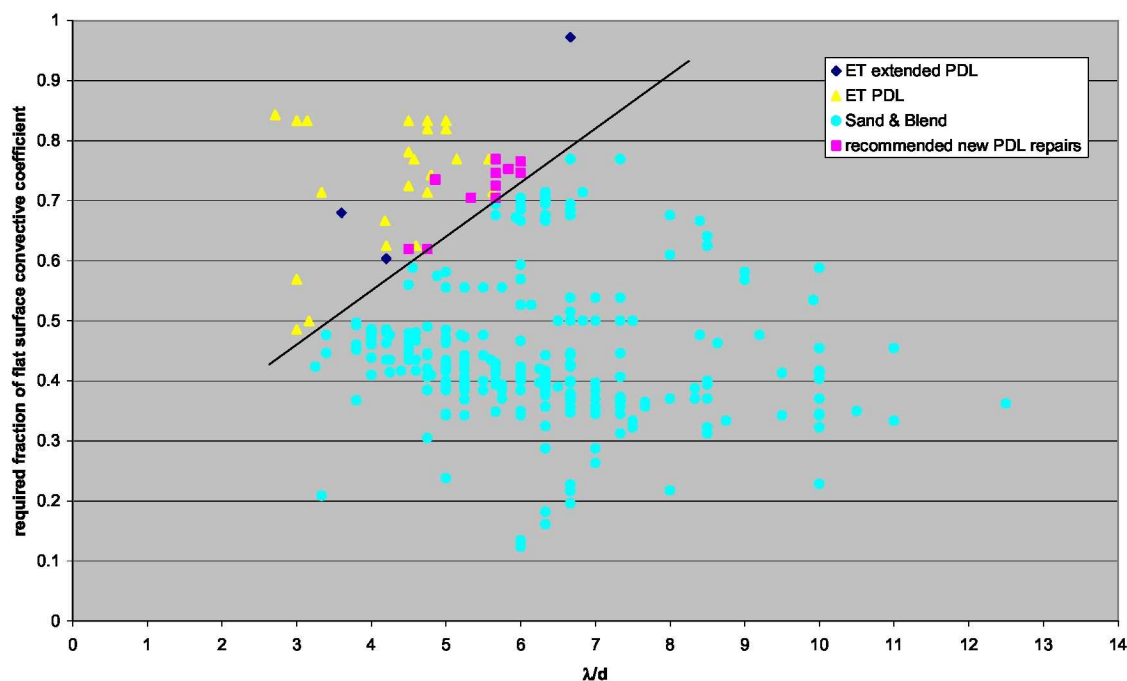



Figure F-6 – Repair Sorting and Recommended Augmentation

Figure J-6 also shows 11 repairs that were recommended as S&B by the ET Project that are above the dividing line and thus have icing potential that exceeds that of sites that had been designated for PDL repair. The NESC recommended to the project that these sites also be repaired with PDL. The ET Project accepted the recommendation.

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Appendix G. NESC Probability of Launch Based on Icing

Rationale

The NESC was concerned that, because tests that were not representative of the launch pad heat transfer physics were used to establish the PDL vs. S&B repair cutoff, the launch probability due to icing could be substantially less than the 85percent May to October requirement. To address this concern, the NESC performed a sensitivity analysis of the heat transfer in the sand and blend repairs using a 30 year KSC weather dataset.

Method

The first step in performing the sensitivity analysis was to obtain the LO₂ ogive average heat transfer coefficient as a function of wind speed using HPSim⁵, the ET Project certified heat transfer coefficient calculation tool. Using 75°F⁶ as the ambient temperature, the ogive heat transfer coefficient was calculated for a range of wind speeds. The result is shown in Figure 1.

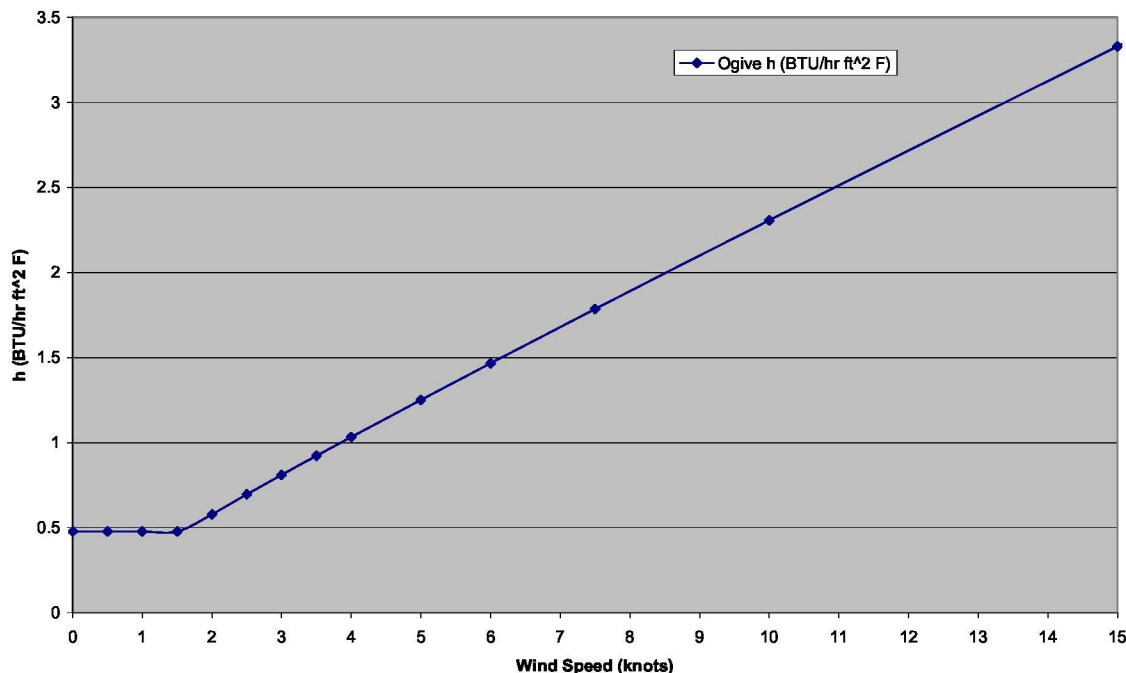



Figure G-1 – Ogive Heat Transfer Coefficient, 75°F Ambient Temperature

⁵ HPSim Rev F, Lockheed Martin Michoud Space Systems

⁶ 75°F is an approximate average for the ambient temperature at KSC between May and October.

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The flat region at low wind speeds in Figure 1 is the natural convection region. At wind speeds above 1.5 knots, forced convection heat transfer dominates. Because the heat transfer coefficient in the dominant forced convection regime is not a strong function of ambient temperature, the HPSim output was curve fit to provide a single valued function of ogive convection coefficient as a function of wind speed.

The thermal resistance network for heat transfer on the ogive with a convective boundary condition is shown in Figure K-2. Here A is a representative area, t is the foam thickness, h is the convective coefficient, k_{eff} is the effective foam thermal conductivity, T_{surface} is the foam outer surface temperature, and T_{∞} is the ambient temperature.

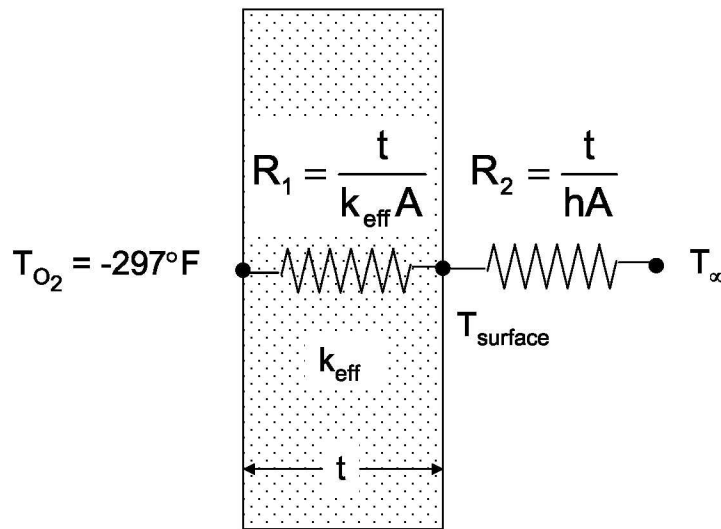



Figure G-2 – Thermal Resistance Network for Ogive Heat Transfer

For a given foam thickness, if the surface temperature is 32°F (the icing limit), the heat flux, q'' , is

$$q'' = \frac{k_{\text{eff}}}{t} (32 + 297)^{\circ}\text{F} \quad (1)$$

The corresponding convective heat transfer is

$$q'' = h(T_{\infty} - 32)^{\circ}\text{F} \quad (2)$$

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If the convective heat transfer is higher than the value in eqn. (2), the higher heat transfer will drive the surface temperature above the freezing point. Therefore, we can use the quantity F as an icing indicator where

$$F = h(T_{\infty} - 32)^p F \quad (3)$$

A 30 year KSC weather data base was obtained from MAF. This database includes hourly observations of ambient temperature and wind speed. For each observation in the database, the convective coefficient curve fit was used to calculate a value of F. The results were then sorted on F. This allowed us to find the value of F that coincides with 15percent icing probability (85percent launch probability) and to assess the probability distribution of F.

The sorted wind speed measurements are shown in Figure 3. Three lines are plotted for 3 separate data subsets owing to Excel limitations. The wind speed probability shows the 1.5 knot wind speed limit for natural convection is exceeded more than 90percent of the time.

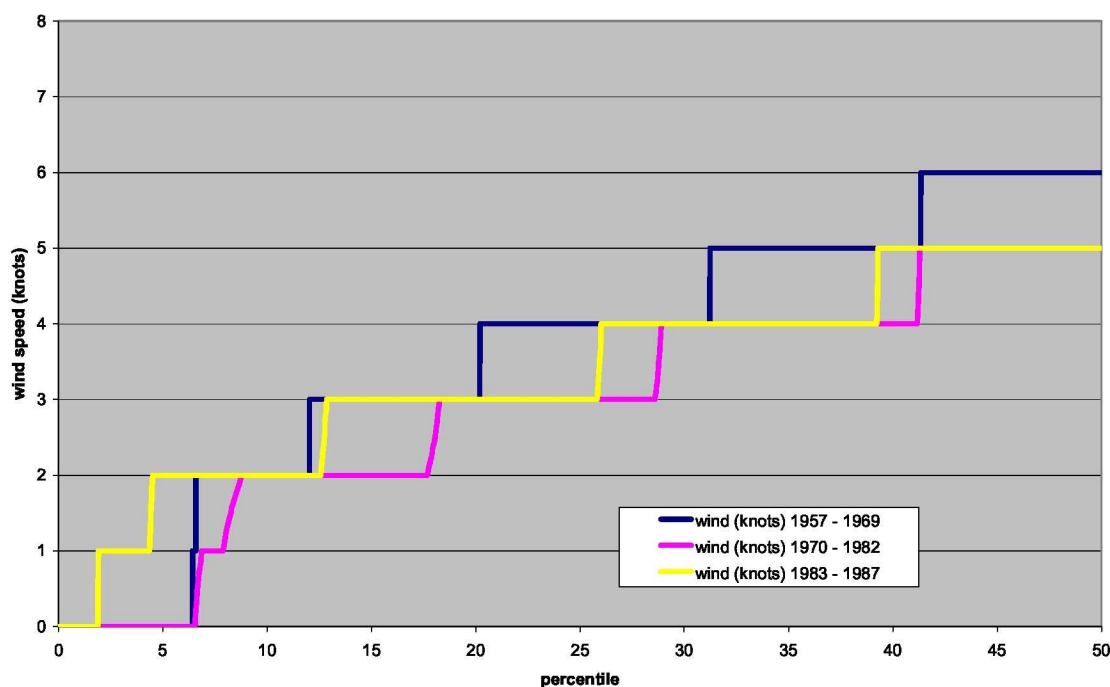



Figure G-3 – May to October Wind speed at KSC

The probability distribution of the icing parameter, F is shown in Figure K-4. Here, also, the data is broken into three data subsets owing to Excel limitations. A single black line is faired

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through the three data subsets. The value of F that coincides with an 85percent icing launch probability is 30 BTU/hr ft².

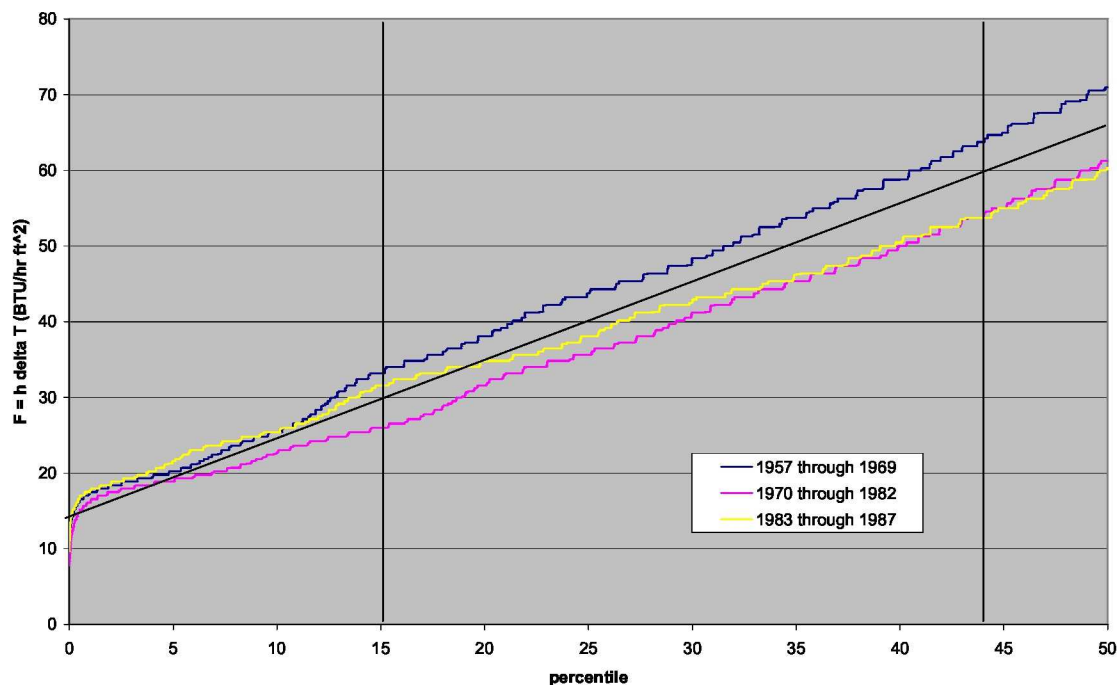



Figure G-4 – Icing Parameter, F – May to October at KSC

The choice between sand and blend repairs and PDL repairs for different hail damage locations was made based on a presumed relationship between the dimensions of the sand and blend cavity and the heat transfer at the bottom of the cavity as was detailed in Appendix F. Figure K-5 shows the selected relationship as a diagonal black line. If this line reflects the relationship between the fraction of flat surface convective coefficient and the geometry parameter, we have maintained 85percent launch probability May-October (per the ET analysis).

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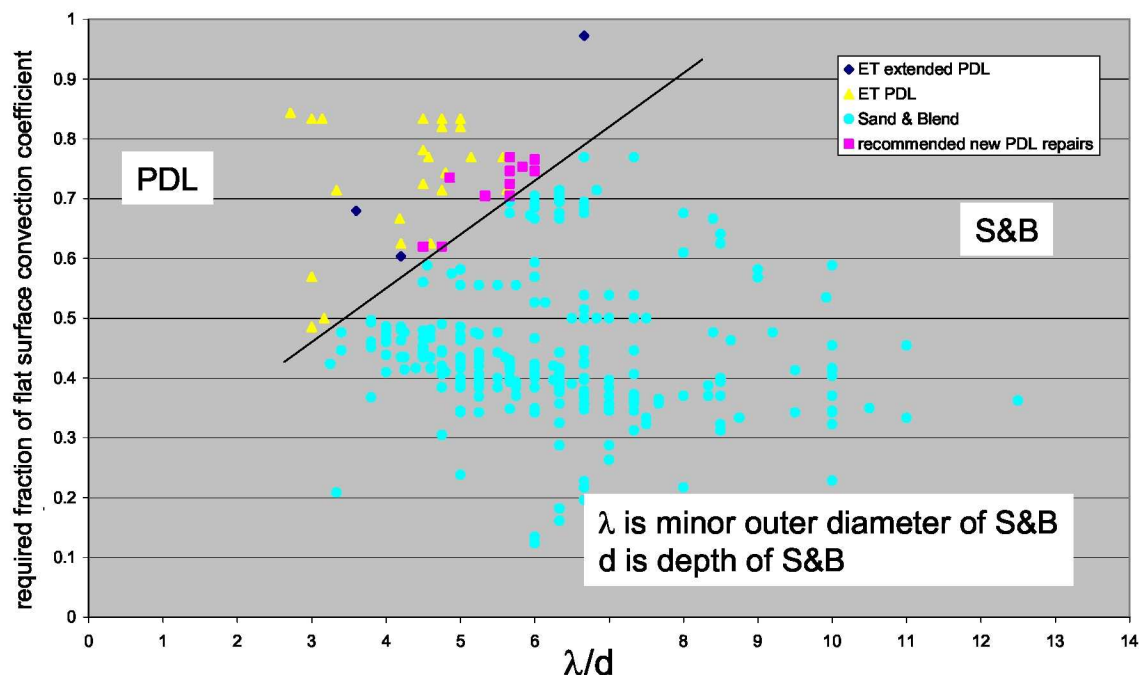



Figure G-5 – Relationship Used to Discriminate between Sand and Blend and PDL Repairs

Figure 4 gives us a method of assessing the launch probability sensitivity to the location of the dividing line in Figure 5. If dividing line is off by a factor of 2, the critical value of F on a flat surface would need to double to prevent icing above the 15percent probability level. Figure 4 shows that if we select the critical value of F as 60 (2x the nominal 15percent level), the icing probability is less than 45percent (and the launch probability still exceeds 55percent). Therefore, we conclude that the selected sand and blend criteria yields a relatively robust icing launch probability.

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Appendix H. NESC Cryogenic Moisture Uptake Core Study

NESC Ice Mitigation Assessment Cryogenic Moisture Uptake (CMU) Core Study

Introduction: CMU Core Study

Material weight gain due to water vapor condensation and permeation under cryogenic conditions was a major consideration of candidate insulation materials. It was deemed critical to understand where the water/ice resides within the foam. If a weight gain occurs in the cold section of foam then ice/frost would be present and liquid water would be present in the warmer sections. A test method was developed that would utilize the CMU test methodology followed by dissection and monitored weight loss to determine water location within the foam. This involved taking multiple core specimens from a foam sample soon after removal from the CMU test. The cores were cut into sections to determine if weigh loss/gain occurred in the warm surface, in the middle region, or the cold surface (see test method).

Test Method: CMU Core Study

Standard CMU tests were conducted with the exception that the test specimen was not removed to monitor weight gain over time. The specimen was only removed on the 8th hour of cold soak to measure the weight followed by dissection and weight measurement of dissected core specimens. Figure 1 below shows approximately how the core sections were taken.

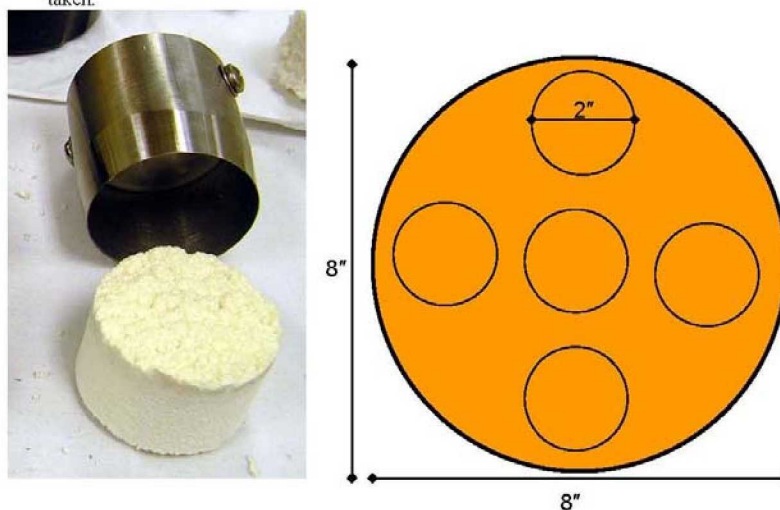



Figure 1. Pictured on the left is the core tool and cored practice sample. CMU core diagram on the right.

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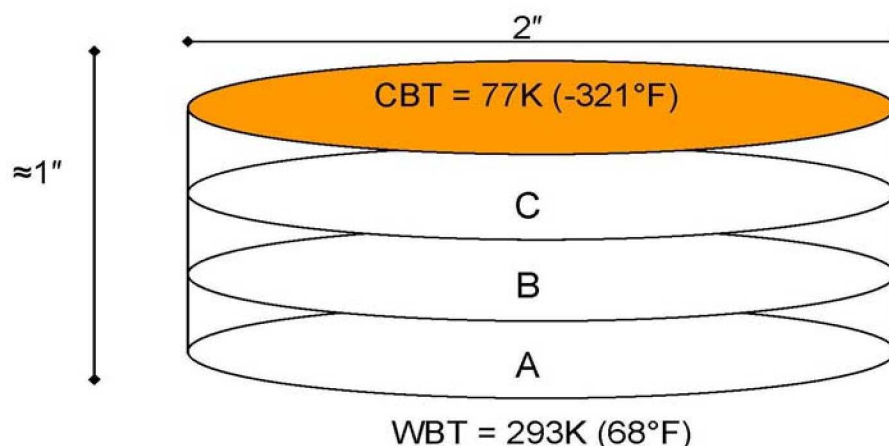



Figure 2. CMU core dissection diagram. Section C contains the cold boundary temperature (CBT) and section A contains the warm boundary temperature (WBT).

A core specimen was drilled out and carefully dissected using a long razor knife. Each core was cut into 3 sections of approximate equal depth. Each section was labeled relative its position during CMU testing. For instance, 1A would be the warm side of core one, 3B would be the middle section of core three, and 4C would be the cryogenic side of core four. Each core section was dissected, labeled, and weighed immediately after being cut from the main 8" diameter sample. Once all samples were weighed they were then placed into a dry nitrogen purged chamber over night. The samples were then re-weighed to determine moisture uptake. Sample total dry weight was verified to the initial dry weight before test.

Results: CMU Core Study

The majority of weight gain was determined to be in the warm section A portion of all cores followed by section B, and finally the least amount of weight gain was found in cold section C. The net spray surface of NCFI 24-124 foam materials behaved differently from that of the machined surface of BX-265. This may have been due the way the samples were cut. Section A took the high points of the rind surface into consideration for dissection. This implies that sections B and C were expanded toward the warm surface (had greater depth) and may therefore explain the decrease in weight of section A relative to the increases in sections B and C. The most surprising results were from the mostly open cell GFT flexible polyimide foam sample (≈30% closed cell). The unrestricted mass transport of water vapor

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meant the weight increase could happen through out the thickness of the foam. Unrestricted mass transport did not change the distribution of water to any great degree; reasons why can be found in the discussion section.



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Table 1. Cryogenic moisture uptake and core data of Baseline BX-265 foam. The foam was not weathered. Core section A data of interest is highlighted in yellow. Final dry weight of the "sample" is the sample left after coring (sample with holes). The sum of the "sample" dry weight with all the core sections comes close to the initial weight; some foam is lost during dissection.

Date:	6/16/2006
Sample:	BX-265 (baseline, not weathered)
Size:	8" o.d. (nominal)
Thickness:	1" (nominal)
Surface:	Flat (both sides)

Thickness (in)	Initial Wt (g) (Dry)	Initial Wt (g) (Wet)	Final Wt (g) (Dry)	Δ Wt (g)	total water in core (g)	water through thickness (%)	avg water through thickness (%)	std dev water through thickness (%)
3-10 Ring	43.102	43.102	43.092					
BX-265 Sample	29.245	30.199	29.896	0.944				
Core (1.A)	0.280	0.75011	0.47008	0.32403		86.6	97.6	0.7
Core (1.B)	0.275	0.49390	0.48738	0.00652		1.9	1.2	0.4
Core (1.C)	0.302	0.69571	0.68041	0.00530	0.33585	1.6	1.1	0.3
Core (2.A)	0.315	0.63720	0.49150	0.32910		86.2		
Core (2.B)	0.295	0.45716	0.45412	0.00304		0.9		
Core (2.C)	0.335	0.60193	0.59802	0.00331	0.34605	1.0		
Core (3.A)	0.298	0.85700	0.53316	0.32384		88.1		
Core (3.B)	0.297	0.49227	0.48822	0.00405		1.9		
Core (3.C)	0.327	0.56997	0.56594	0.00303	0.33002	0.9		
Core (4.A)	0.292	0.55620	0.48482	0.37118		87.7		
Core (4.B)	0.310	0.49178	0.48723	0.00455		1.2		
Core (4.C)	0.365	0.64356	0.63828	0.00528	0.38801	1.1		
Core (5.A)	0.293	0.81753	0.49550	0.32603		87.8		
Core (5.B)	0.325	0.56852	0.56235	0.00617		1.2		
Core (5.C)	0.328	0.52998	0.52622	0.00376	0.33598	1.1		
Avg Thickness	0.312							

Total Wt

72.347	81.291	71.67383
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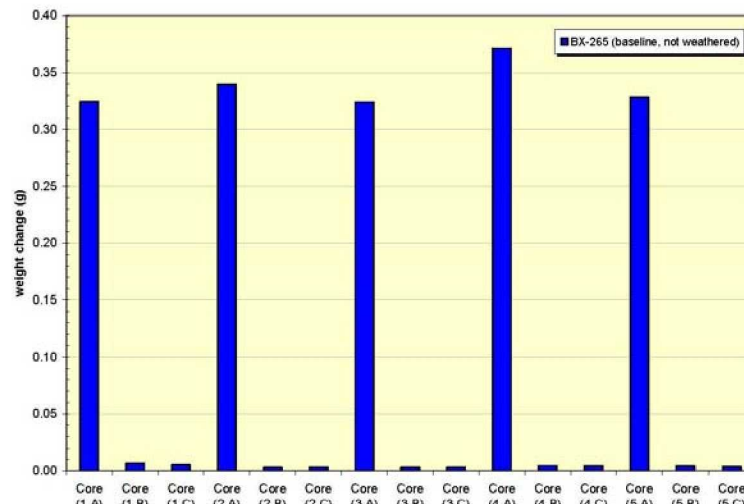



Figure 3. Cryogenic moisture uptake and core data of Baseline BX-265 foam. Foam core sections were weighed after 8 hours of CMU then re-weighed after drying over night in a dry nitrogen purged chamber.

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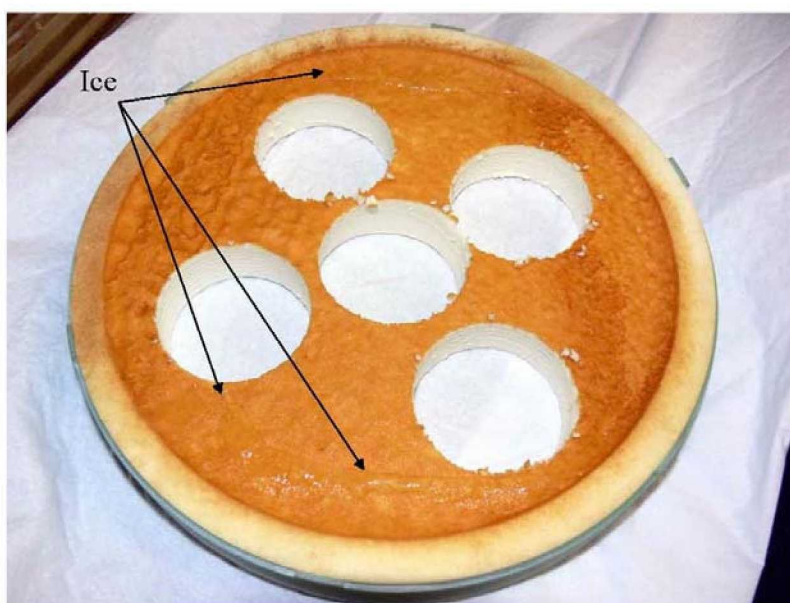



Figure 5. Photograph of 15 month weathered BX-265 foam immediately after all core sections were taken. Note that ice from CMU testing was still present.

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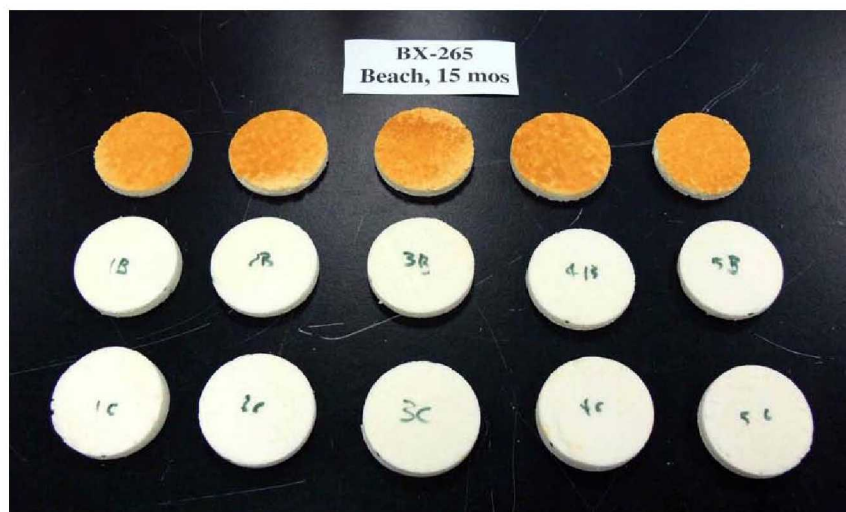


Figure 6. Photograph of dissected cores of BX-265 15 month weathered after drying.



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Table 3. Cryogenic moisture uptake and core data of net spray baseline NCFI 24-124 foam. The foam was not weathered. Core section A data of interest is highlighted in yellow. Final dry weight of the "sample" is the sample left after coring (sample with holes). The sum of the "sample" dry weight with all the core sections comes close to the initial weight; some foam is lost during dissection.

Date:	6/23/2008
Sample:	NCFI 24-124 Baseline
Size:	8" x 8" (nominal)
Thickness:	1.25" (nominal)
Surface:	Kind (Top), Flat (Bottom)

Thickness (in)	Initial Wt (g) (Dry)	Initial Wt (g) (Wet)	Final Wt (g) (Dry)	Δ Wt (g)	total water in core (g)	water through thickness (%)	avg water through thickness (%)	stddev water through thickness (%)
G-10 Ring	37.810	37.810	37.787					
NCFI 24-124 Sample	41.070		28.388					
Core (1,A)	0.400	0.94565	0.62081	0.31479		80.5	83.7	5.5
Core (1,B)	0.441	0.95231	0.76915	0.08316		16.2	43.3	5.5
Core (1,C)	0.387	0.79239	0.77941	0.01298	0.39030	3.3	3.0	0.3
Core (2,A)	0.341	0.84680	0.51524	0.33156		76.1		
Core (2,B)	0.437	0.95983	0.76902	0.09081		20.9		
Core (2,C)	0.500	0.84962	0.82715	0.01347	0.43564	3.1		
Core (3,A)	0.417	1.06514	0.70414	0.36100		84.4		
Core (3,B)	0.390	0.78912	0.74510	0.04342		12.5		
Core (3,C)	0.377	0.74933	0.73800	0.01133	0.42775	3.1		
Core (4,A)	0.471	1.09225	0.69919	0.39307		88.1		
Core (4,B)	0.411	0.72300	0.69271	0.03029		8.0		
Core (4,C)	0.451	0.72884	0.72536	0.01248	0.43484	2.9		
Core (5,A)	0.444	1.14795	0.76456	0.38342		89.6		
Core (5,B)	0.392	0.76940	0.73564	0.03376		7.9		
Core (5,C)	0.403	0.69276	0.69267	0.01082	0.42801	2.5		
Avg Thickness	0.421							
Total Wt		79.88	77.981					

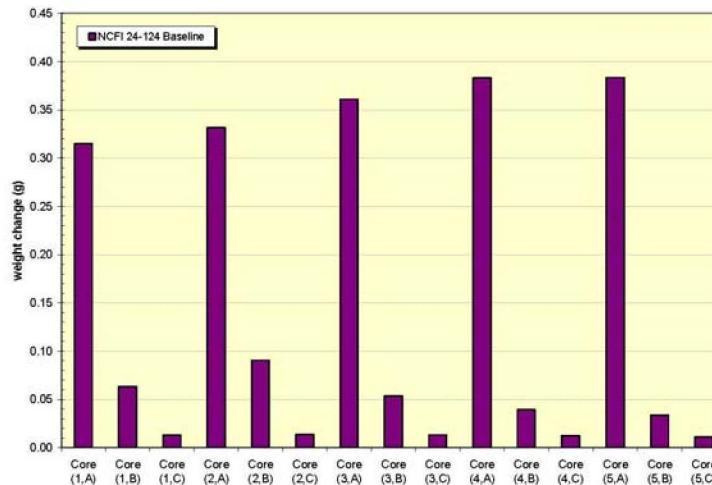


Figure 7. Cryogenic moisture uptake and core data of baseline net spray NCFI 24-124 foam. Foam core sections were weighed after 8 hours of CMU then re-weighed after drying over night in a dry nitrogen purged chamber.



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Table 4. Cryogenic moisture uptake and core data of 15 month weathered net spray NCFI 24-124 foam. Core section A data of interest is highlighted in yellow. Final dry weight of the "sample" is the sample left after coring (sample with holes). The sum of the "sample" dry weight with all the core sections comes close to the initial weight; some foam is lost during dissection.

Date:

6/22/2006

Sample:

NCFI 24-124 Weathered (15 mos)

Size:

3" o.d. (nominal)

Thickness:

1.25" (nominal)

Surface:

Wind (Top), F18 (bottom)

Thickness (in)	Initial Wt (g) (Dry)	Initial Wt (g) (Wet)	Final Wt (g) (Dry)	Δ Wt (g)	total water in core (g)	water through thickness (%)	avg water through thickness (%)	std dev water through thickness (%)
G-10 Ring	43.102	43.102	43.100					
NCFI 24-124	38.492	36.441	26.013	19.849				
Core (1.A)	0.234	1.75207	0.43653	1.31544		92.6	1.7	
Core (1.B)	0.265	0.63653	0.72305	0.10018		6.6	1.7	
Core (1.C)	0.263	0.85974	0.84734	0.01140	1.42902	0.8	0.7	
Core (2.A)	0.237	1.89365	0.45696	1.43269		84.7		
Core (2.B)	0.241	0.81340	0.73520	0.07820		9.1		
Core (2.C)	0.348	0.63709	0.82708	0.01001	1.52110	0.7		
Core (3.A)	0.231	1.71569	0.41841	1.29948		80.7		
Core (3.B)	0.275	0.94832	0.82595	0.12238		8.5		
Core (3.C)	0.313	0.76095	0.77940	0.01155	1.43341	0.6		
Core (4.A)	0.253	1.83845	0.50063	1.33782		84.5		
Core (4.B)	0.224	0.81758	0.76183	0.05565		4.6		
Core (4.C)	0.319	0.77802	0.76622	0.00880	1.20357	0.6		
Core (5.A)	0.251	1.61887	0.40112	1.23855		81.2		
Core (5.B)	0.347	0.88778	0.78588	0.10187		7.7		
Core (5.C)	0.302	0.79959	0.79248	0.00710	1.31852	0.6		
Avg Thickness	0.269							
Total Wt		79.594	99.543	78.182				

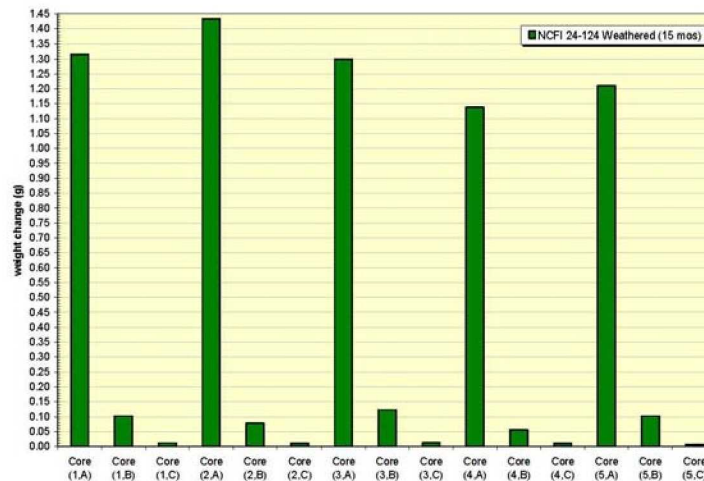


Figure 8. Cryogenic moisture uptake and core data of 15 month weathered net spray NCFI 24-124 foam. Foam core sections were weighed after 8 hours of CMU then re-weighed after drying over night in a dry nitrogen purged chamber.



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Figure 9. Photograph of 15 month weathered net spray NCFI 24-124 after coring and drying overnight.

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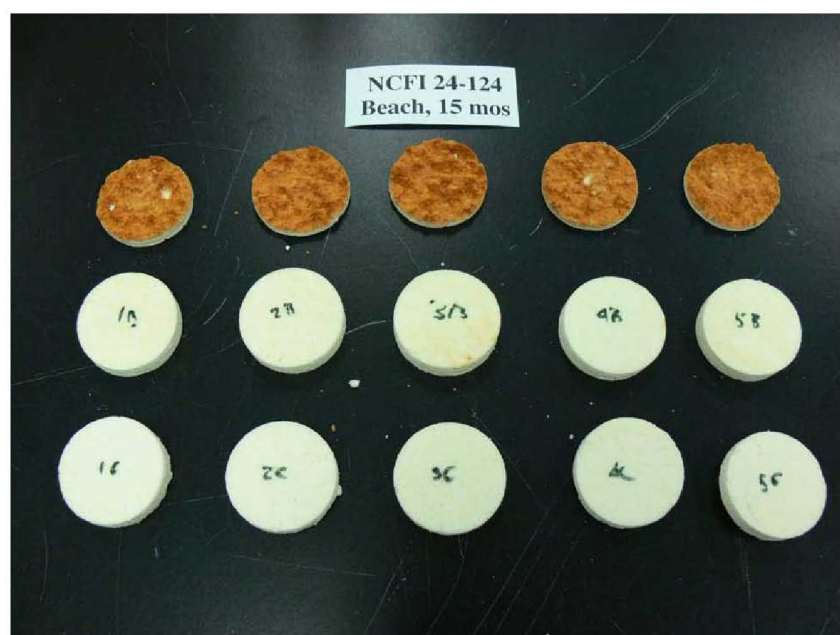


Figure 10. Photograph of dissected cores of net spray NCFI 24-124 15 month weathered samples after drying.



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Table 5. Cryogenic moisture uptake and core data of 2 year indoor aged GFT flexible polyimide foam. The foam was not weathered. Core section A data of interest is highlighted in yellow. Final dry weight of the "sample" is the sample left after coring (sample with holes). The sum of the "sample" dry weight with all the core sections comes close to the initial weight; some foam is lost during dissection.

Date:	6/29/2006
Sample:	GFT 2 years old
Size:	8" o.d. (nominal)
Thickness:	1.25" (nominal)
Surface:	Rnd (Top), Flat (Bottom)

Thickness (in)	Initial Wt (g) (Dry)	Initial Wt (g) (Wet)	Final Wt (g) (Dry)	Δ Wt (g)	total water in core (g)	water through thickness (%)	avg water through thickness (%)	stddev water through thickness (%)
G-10 Ring	43.101	43.260	43.101					
GFT Foam	16.646	30.344	11.629	13.598				
Core (1,A)		1.06104	0.33567	0.72537		96.1	96.3	0.5
Core (1,B)		0.35605	0.32024	0.03581		3.9	3.4	0.5
Core (1,C)		0.32084	0.32083	0.00001	0.76119	0.0	0.4	0.5
Core (2,A)		1.00972	0.35569	0.73383		95.0		
Core (2,B)		0.34505	0.31376	0.03127		4.1		
Core (2,C)		0.26927	0.26859	0.00078	0.76586	0.1		
Core (3,A)		1.07789	0.34803	0.72866		86.3		
Core (3,B)		0.34660	0.32753	0.01907		2.5		
Core (3,C)		0.30277	0.29369	0.00888	0.75601	1.2		
Core (4,A)		1.64430	0.37056	1.17374		98.9		
Core (4,B)		0.36408	0.32896	0.03512		2.9		
Core (4,C)		0.28525	0.28322	0.00203	1.21089	0.2		
Core (5,A)		1.12370	0.36304	0.76066		44.4		
Core (5,B)		0.46470	0.29227	0.17243		22.6		
Core (5,C)		0.38320	0.34116	0.04204	0.97813	4.3		
Avg Thickness								
Total Wt	59.747	73.504	59.618					

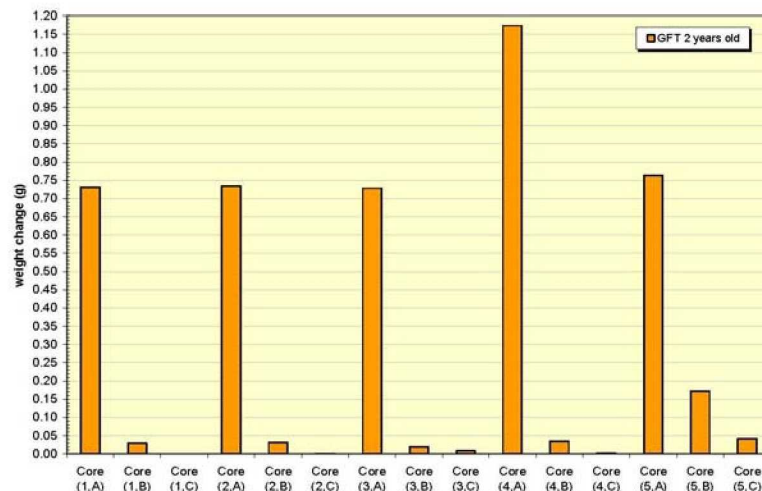


Figure 11. Cryogenic moisture uptake and core data of 2 year indoor aged GFT flexible polyimide foam. Foam core sections were weighed after 8 hours of CMU then re-weighed after drying over night in a dry nitrogen purged chamber.


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Figure 12. A photograph of GFT flexible polyimide foam immediately after removal from Cryogenic Moisture Uptake test apparatus. Note the ice/frost and water drops evident on the warm surface.


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Figure 13. A photograph two minutes after removal from CMU apparatus the first core was drilled out. Note the ice/frost section.



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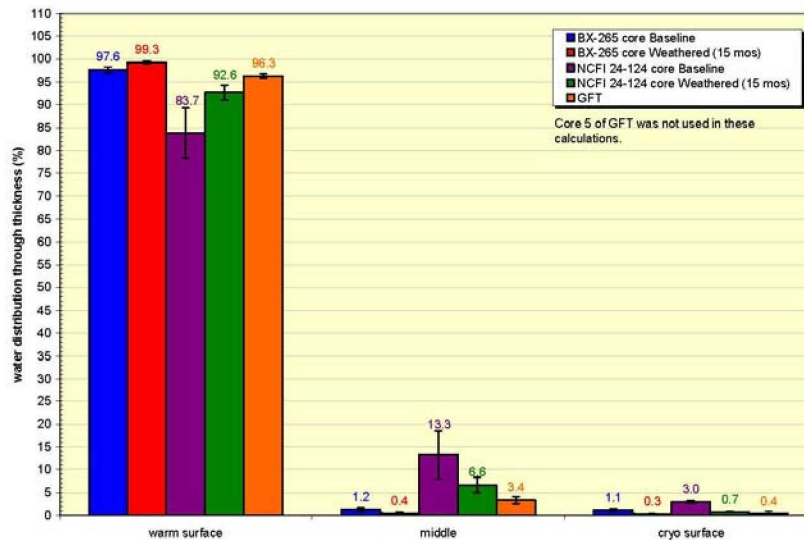



Figure 16. Core data of all samples. Core data strongly indicates that though samples had different amounts of water weight gain how the water was distributed was remarkably similar. The 5th core for GFT was omitted because it was deemed an outlier.


Discussion: CMU Core Study

Test results indicate that weathered foams have higher water/ice weight gain. Based on these results a larger percentage of the water/ice weight gain remains near the surface (section A) for the weathered versus non-weathered foams tested. BX-265 is better in this regard, because there is very little weight in sections B and C, though more extensive studies are required to make such conclusions.

Test results indicate that water distribution throughout the thickness of “closed cell” foam samples in comparison to “open cell” foam samples was similar. Frost formation and liquid water condensation are simply a function of dew point, surface temperature, and surface area. Water/frost deposition does change the local humidity level within the foam thus to maintain equilibrium humidity conditions water vapor does need to transport to the localized area with reduced humidity. This mass transport seems to be a small driver as indicated by the data (Figure 16.). Though the GFT foam has the ability from a mass transport point of view to gain weight in cryogenic section C and middle section B that does not occur. What probably occurs in these cold sections is that all of section C is below

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freezing and most of section B is below freezing thus only low density frost can form. Testing is underway to verify this hypothesis. One implication of this hypothesis is that hard ice formation might not be such a problem within open cell foam materials. Hard ice will only form at the melt/freeze line and requires a decrease in ambient temperature or a decrease in cryogenic temperature. Any decrease in temperature will drive the freeze line out toward the warm surface thus freezing any liquid condensate. In fully hydrophobic foam systems small spheres of ice would likely form inboard of an outboard advancing freeze line. Tests are under development to characterize type of ice formation within foam systems.

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Appendix I. NESC Expected PDL 1034 Mass Loss Assessment

Summary

One of the facets of the flight rationale for STS-117 is the probability risk assessment (PRA). This assessment uses a Monte Carlo technique to calculate the risk to the Orbiter from the expected level of ascent debris. Once the 900+ PDL 1034 repairs were completed on the tank, the values for the maximum expected ascent foam loss from each repair could be developed. The ET Project developed a database of maximum expected foam loss from the PDL 1034 repairs using the following procedure:

1. The mass of each PDL 1034 repair was calculated from the repair height, width, and length assuming a brick shaped repair.
2. The database was sorted to retain only the repairs with masses greater than 0.004 lbm, the Orbiter deterministic foam debris limit.
3. The maximum expected divot mass was then calculated using the maximum expected cylindrical defect⁷ placed at either its maximum devoting depth or the depth of the repair, whichever was less.

The result was a list of 86 divots from the 900+ repairs with masses ranging from 0.006 to 0.028 lbm.


The NESC was concerned that this calculation technique did not include the fact that repairs of less than 0.004 lbm can throw divots greater than 0.004 lbm owing to the angle of the divot cone. Also, it was not clear whether the possibility of slot defects had been included in the ET Project's calculation.

Therefore, the NESC repeated the ET Project analysis with two critical differences:

1. All PDL 1034 repairs were evaluated for divoting.
2. Both slot and cylinder voids were assessed.

The resulting list of maximum expected slot and cylinder divots for each location was then sorted for the maximum expected (i. e., whether from a slot or cylinder). Of the 900+ PLD 1034 repairs, 747 could generate divots larger than 0.004 lbm deterministic limit - a number substantially larger than the 86 generated by the ET Project. The NESC recommended to the Space Shuttle Systems Engineering and Integration (SE&I) Office that the NESC method be used to capture the maximum expected divot masses from the PDL 1034 repairs. The SE&I Office accepted the recommendation.

⁷ The maximum expected defect is assessed from the available dissection data. The maximum void size observed in the dissections is increased by 40% to obtain the maximum expected defect.

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Method

The pressure difference between a sealed void and the external atmosphere cause a divot to occur during the Space Shuttle's ascent. This void-delta p divoting mechanism was studied extensively during the post-Columbia return to flight effort. Divot/No-Divot curves were developed from test data from each type of foam on the External Tank that could be used to predict the maximum divoting depth for any sized void of the two characteristic void types, slots and cylinders.

Once the 900+ PDL 1034 repairs were completed on ET 124, the length, width, and depth were known for each repair. This geometry information, the maximum expected size of cylinder and slot defects, plus the Divot/No-Divot curves could be used to calculate the maximum expected void size.

The detailed methodology used for cylindrical defects was:

1. The cylindrical defect diameter taken as 1.5 inches (the maximum expected diameter) or the largest repair dimension (length or width), whichever was smaller.
2. The void depth was set at either the repair depth or its maximum divoting depth according to the cylinder Divot/No-Divot curve, whichever was smaller.
3. The divot volume was calculated using a frustum with cone angle of 30° from the foam free surface as recommended by the ET Project. The minimum frustum diameter was the cylindrical defect diameter.
4. The divot mass was calculated using the ET Project provided PDL 1034 density of 3.44 lbm/ft³.

The detailed methodology used for slot defects was:

1. The slot length was taken as largest repair dimension (length or width).
2. The slot defect diameter was taken as 0.84 inches (the maximum expected diameter) or the length/2.4, whichever was smaller⁸.
3. The void depth was set at either the repair depth or its maximum divoting depth according to the slot Divot/No-Divot curve, whichever was smaller.
4. The divot volume was calculated using a translated frustum with cone angle of 45° from the foam free surface as recommended by the ET Project. The minimum frustum diameter was the slot defect diameter. The full length of the solid was the slot length.
5. The divot mass was calculated using the ET Project provided PDL 1034 density of 3.44 lbm/ft³.

The cylinder and slot divot masses each PDL 1034 repair were then compared to determine whether the maximum divot mass was the result of a slot or cylinder defect. The largest mass was selected for reporting⁹.

⁸ At length/diameter ratios less than 2.4, a slot is considered to be a cylinder.


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Figure L-1 plots the divot masses generated by the ET Project analysis and the NESC analysis. Even the figure shows that a very large number of possible divots greater than the deterministic limit of 0.004 lbm are not calculated are by the ET Project's algorithm.

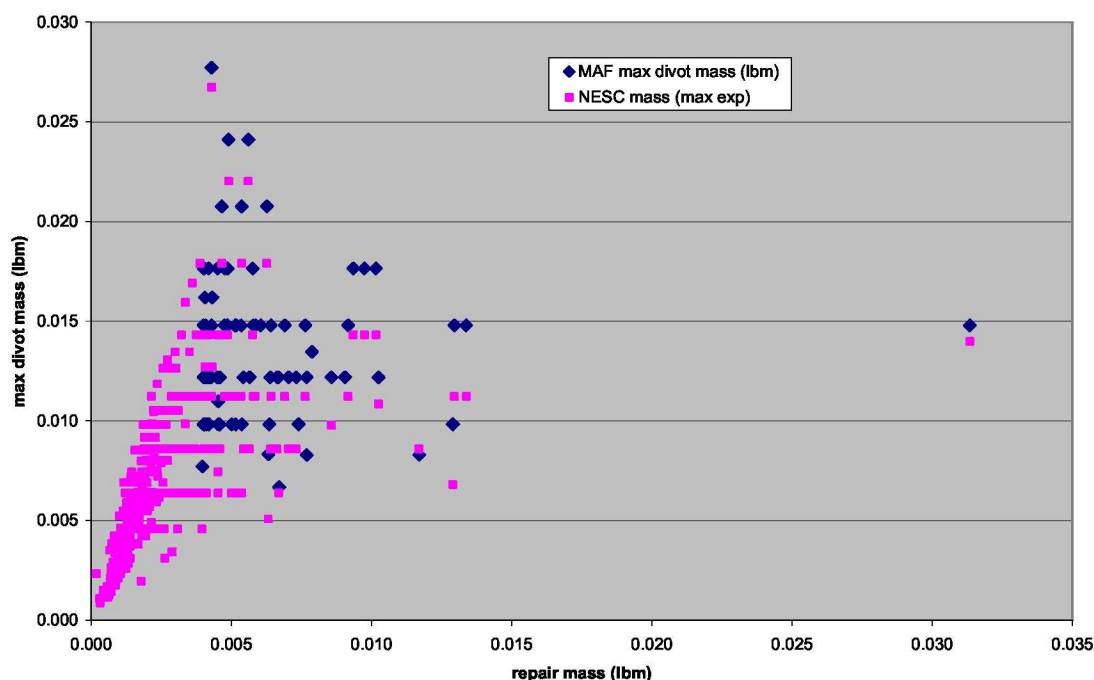



Figure I-1 - Maximum Expected Divot Masses Using the Two Algorithms

Figure L-2 plots sorted defect masses greater than 0.004 lbm obtained by the two algorithms. The figure shows the additional smaller masses between 0.004 and 0.010 lbm that are captured by the NESC method.

⁹ The slot void yielded the highest mass for only four of the repairs assessed, cylindrical defects yielded the largest masses for the remainder.

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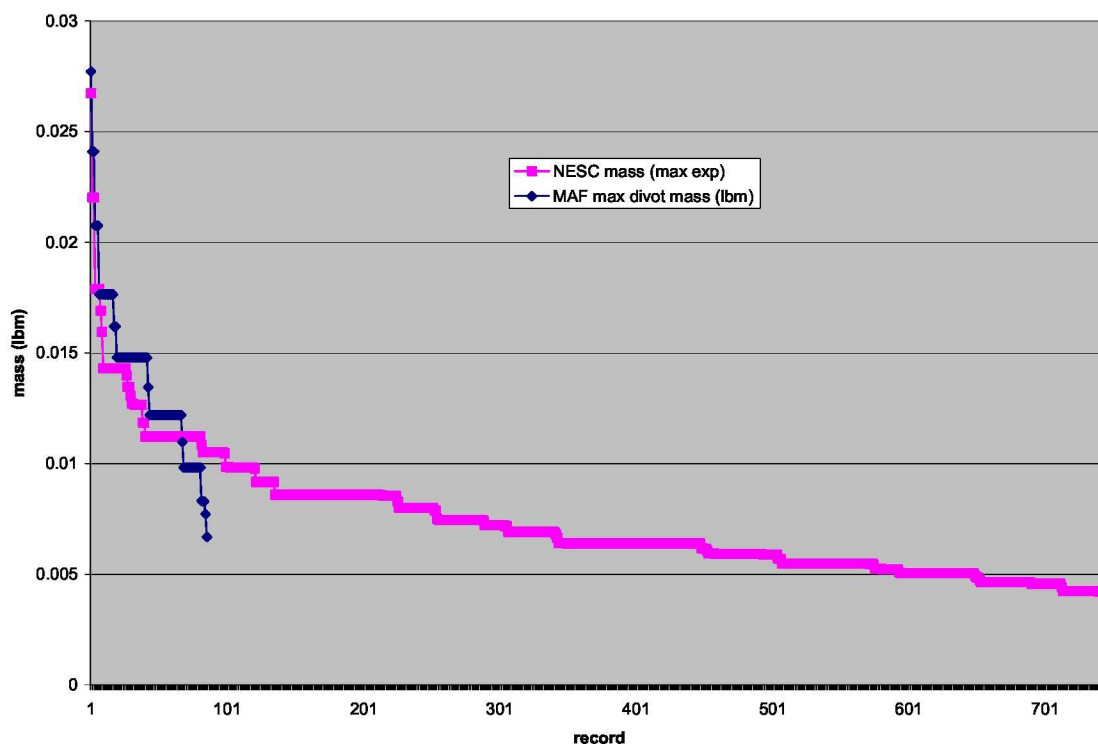



Figure L-2 – Sorted Divot Masses

Using the NESC method allows all the maximum expected divots that exceed 0.004 lbm to be captured, generating the most accurate possible input to the PRA. The NESC recommended to the Space Shuttle Systems Engineering and Integration (SE&I) Office that the NESC method be used to capture the maximum expected divot masses from the PDL 1034 repairs. The SE&I Office accepted the recommendation.

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Appendix J. Evaluation of the Inspection of Nose Cone, GH2 Pressurization Line Fairing, and Intertank Access Door for ET 124

Summary:

Inspection of the ET 124 Composite Nose Cone at KSC using the MSFC Thermal Wave Imaging (TWI) thermography system was of better quality than the original inspection for manufacturing acceptance. This is because the original acceptance used a thermography system with a poorer resolution and sensitivity. Inspectors were as well qualified and certified as those that performed the original acceptance inspection. Access to the Nose Cone was adequate to allow complete inspection. The critical initial flaw size (CIFS) was large in comparison to the damage in the NDE calibration impact damage coupons used to verify detection capability of the thermography system. During initial development, the capability of the Nose Cone to perform adequately with an included CIFS defect was verified by a damage tolerance test program prior to incorporating the Composite Nose Cone on the External Tank. Impact of a critical level would leave a visible dent on the surface of the Nose Cone. No visible indications were found upon visual examination of the Nose Cone. The thermography images from the inspection were reviewed an additional time by two more MSFC inspectors with no reportable indications found.

Inspection of the GH2 Pressurization Line Fairing, and Intertank Access Door for ET 124 used hand held ultrasonic inspection. No review of data was possible as none was stored during the inspection. The initial acceptance inspection for the Pressurization Line Fairing was also hand held ultrasonic inspection. So the reinspection of this part was of similar quality to the initial acceptance inspection. However, the initial acceptance inspection of the Intertank Access Door uses a better quality inspection, C-scan ultrasound. This fact needs to be considered for relevance for the flight worthiness decision.

Information on the inspection of the metal louver of the Nose Cone has been requested from Lockheed Martin MAF. An assessment of this inspection will be added at a later date.


Supporting Material:

The thermography images taken during the ET Nose Cone inspection were reviewed by Joseph Ragasa and Sam Russell on May 22 and 23, 2007.

A Telecom with Carl Bouvier occurred on May 10, 2007 and James Walker joined me in my office.

On the ET Nose Cone

Mr. Bouvier and Mr. Walker conducted the thermography inspection on March 17 and 18, 2007. Mr. Ricky Clements represented SM&A and assisted in moving the inspection head and tripods.

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Visual inspection of the three ET parts was performed by Kevin Vega (NASA), Ahmad Ekhlassi (USA), and Carl Bouvier (LM MAF) on March 6 2007.

Mr. Bouvier has level III certification in ultrasonic and thermography inspection. He has passed a recent vision test using the Jaeger 2 at 12" or more method.

The MSFC owned Thermal Wave Imaging (TWI) Flash thermography System was used. This system uses a FLIR Phoenix camera with 25 mm lens, TWI lamps, TWI computer, and TWI Echotherm 6.2 software used. Image subtraction of preflash was used. The Phoenix camera has thermal sensitivity of 0.02 degrees K, and an Indium Antimonide 640 X 512 pixels array detector operating to detect 3-5 micro meter infrared light. Full sequence of tw2 images was stored at each inspection location.

The Nose Cone had been dry dusted with a cloth prior to beginning inspection.

No coating for emissivity control was used. The finish was the normal as processed finish.

Metal tape indicators marked 7" x 7" grids.

Four NDE coupons made from an early non-production Nose Cone were used to verify detectability of impact damage. These 3" x 3" coupons had been impacted by a cylindrical, round faced impactor at 3.3, 8.8, 5.2, and 6.6 ft lb of energy. Several other coupons were available that contained high energy impacted zones but were not used. The damage zones in the coupons were easily detected with the TWI thermography system. The impact at the 3.3 ft lb level specimen resulted in a barely visually detectable indentation on the front surface. The damage zone on this specimen was measured by the Thermography system to be 0.49" on the front and 0.94" on the back in diameter.

The coupons were inspected at different distances and up to a 60 degree angle to the normal and all damage zones were detectable.


Initial acceptance of the Nose Cone was with thermography using an Inframetrics 760 camera.

A set of heat lamps is positioned at 90 degrees to the Nose Cone with the Cone attached to a turntable. The Cone is rotated at about 1 rpm. This is somewhat equivalent to flash thermography. The Inframetrics 760 camera is a scanning system with a single Mercury Cadmium Telluride detector. The thermal sensitivity is 0.1 degree K detecting 8 - 12 micro meter infrared light.

Nose Cone is 18 plies thick at bottom, 24 plies thick at top, about ¼ inches thick.

On Pressurization Line Fairing

Material is graphite epoxy. 6 to 10 plies thick. The part is approximately 12" long by 6" wide by 6" high.

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Inspected April 12, 2007 with hand scanned ultrasonics, with 5 MHz, 0.25" transducer by Carl Bouvier (LM MAF). Inspection was operated in pulse-echo mode off the back-surface using water squirter-bottle to control coupling.

A defect standard of a fairing containing Teflon inserts was used to tune pulser/receiver. Set up with back surface Teflon inserts at 80% of full screen height (FCH). The base noise level is less than 10% FSH.

No grid was used, just hand raster scan. The scan was done twice. The part was at head height when standing on small stool. Access to the part was unrestricted. The part flange could not be inspected because of interference of attachment bolts.

Inspection was witnessed by Ricky Clements (MSFC) and James Walker (MSFC).

Manufacturer used hand scan ultrasonic inspection for acceptance. Critical initial defect is ¼" x ¼".

On Intertank Access Door

Material is graphite epoxy, skin stiffened with bonded hat shaped vertical stringers.

Inspected April 12 2007 with hand scanned ultrasonics, with 5 MHz, 0.25" transducer by Carl Bouvier (LM MAF). Inspection was operated in pulse-echo mode off back-surface using water squirter-bottle to control coupling.

A defect standard of a section of door containing Teflon inserts was used to tune pulser/receiver. Set up with back surface Teflon inserts at 80% of full screen height (FCH). Noise level is unknown.

No grid was used, just hand raster scan. The scan was done twice. Part was at knee to shoulder height.

Inspection was witnessed by Ricky Clements (MSFC) and James Walker (MSFC).

Manufacturer used C-scan ultrasonic inspection for acceptance. Critical initial defect is ¼" x ¼".

Telecom with Bobby Biggs (LM) on May 14, 2007


Discussion was on the development program for the Composite ET Nose Cone.

A damage tolerance program was used to satisfy fracture control requirements.

Flat coupon tests examined different types of damage. Impact was found to be the most significant damage in effecting compression strength.

A 20 ft-lb impact with ½" diameter cylindrical impactor was found to cause barely visible damage.

Compression tests of coupons were conducted from -320 to 800 degrees F. The trend was for the impact to affect the compression property the same for all temperatures.

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Full scale testing was conducted on cone with four 20 ft-lb impacts located in critical areas. This cone was tested to simulated loads for four flights lives and more than 3 times the maximum flight load once with no damage growth measured by ultrasonic inspection.

A 20 ft-lb impact caused 2.5” diameter damage zone in coupons and 1” to 2” diameter damage zone in the full scale cone.

1” by 1” critical defect size was developed from the damage tolerance program.

May 17, 2007

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14. ABSTRACT Severe thunderstorms with associated hail and high winds struck the STS-117 stack on February 26, 2007. Peak winds were recorded at 62 knots with hail sizes ranging from 0.3 inch to 0.8 inch in diameter. As a result of the storm, the North Carolina Foam Institute (NCFI) type 24-124 Thermal Protection System (TPS) foam on the liquid oxygen (LO2) ogive acreage incurred significant impact damage. The NCFI on the ET intertank and the liquid hydrogen (LH2) acreage sustained hail damage. The Polymer Development Laboratory (PDL)-1034 foam of the LO2 ice frost ramps (IFRs) and the Super-Lightweight Ablator (SLA) of the LO2 cable tray also suffered minor damage. NASA Engineering and Safety Center (NESC) was asked to assess the technical feasibility of repairing the ET TPS, the reasonableness of conducting those repairs with the vehicle in a vertical, integrated configuration at the Kennedy Space Center (KSC) Vehicle Assemble Building (VAB), and to address attendant human factors considerations including worker fatigue and the potential for error. The outcome of the assessment is recorded in this document.					
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